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Spectroscopic Detector Amplifier for 100Hz to 10kHz

R. W. G. CLARKE AND I. P. RUSSELL
Mullard Research Laboratories

This article describes an 800Hz tuned amplifier which has been designed to amplify the electronic signals from any of the following detecting devices: the 150UVP, 150CVP and XP1002 photomultipliers; the 120CPY lead sulphide detector; the ORP10 and ORP13 indium antimonide detectors; the RPY37 and RPY40 copper-doped germanium detectors; and the recently developed 802CPY triglycine sulphate detector (TGS). Together these detectors cover the spectral range from the ultraviolet, through the visible and near infrared, to wavelengths in excess of 25μm.

INTRODUCTION

The amplifier described in this article has been designed to be used with a wide range of spectroscopic detectors which have response times of about one millisecond or less. An experimental version of the amplifier has been constructed and tested with the following detectors:

1)	Photomultipliers	150UVP, 150CVP and XP1002
2)	PbS	120CPY
3)	InSb	ORP13 (cooled) and ORP10 (room temperature)
4)	Cu-doped Ge	RPY37, RPY40, used with the recommended head amplifier
5)	Triglycine sulphate	802CPY.

The amplifier noise level is considerably below the detector noise level.

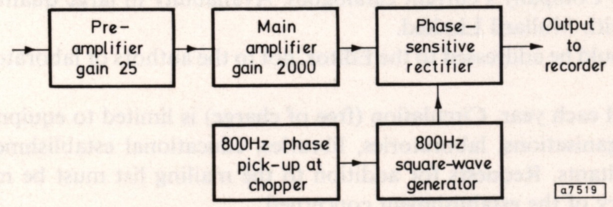

Pre-amplifier gain 25
Main amplifier gain 2000
Phase-sensitive rectifier
Output to recorder
800Hz phase pick-up at chopper
800Hz square-wave generator
a7519

Fig. 1—Block diagram of entire amplifier

The radiation falling on any one of these detectors is chopped at the conventional frequency of 800Hz. The resulting electrical signal from the detector is amplified to a maximum of 5V peak-to-peak by a low noise preamplifier and main amplifier, and then phase-sensitive rectified to give an output of 1V d.c. (Fig. 1).

A phase-sensitive rectifier is used rather than a conventional diode rectifier since this method of rectification can considerably improve the signal-to-noise ratio of a small signal.

A reference waveform is required in order to operate the phase-sensitive rectifier. This may be conveniently generated by placing a semiconductor infrared emitting diode and phototransistor at the chopper and passing the resulting signal to a reference square-wave generator.

The complete amplifier is not limited to 800Hz, but can be readily tuned and used in the range from 100Hz to 10kHz.

PREAMPLIFIER

The preamplifier stage (Fig. 2) consists of a set of detector current biasing networks followed by a conventional valve amplifying stage, this being directly coupled to a cathode follower.

The preamplifier has an input impedance of the order of 10MΩ, a maximum gain of 25 and a very low noise level. The potentiometer controls the overall gain of the amplifier. The 1Ω resistor limits the minimum gain so that 1V peak-to-peak input to the preamplifier, with the potentiometer at zero, will produce a full scale deflection on the amplifier output meter (that is, 1V d.c.). This gives a warning when the photomultipliers are being overloaded by radiation chopped at 800Hz. The d.c. light level (that is, background) must, of course, be kept as low as possible.

It is essential to use wire wound and high stability resistors as indicated in Fig. 2.

MAIN AMPLIFIER

The main amplifier (Fig. 3), which has a fixed overall gain of 2000, is tuned to 800Hz with a bandwidth of 140Hz (3dB). It is composed of two sections with separate feedback loops. The first section, TR$_1$ and TR$_2$, has a gain of approximately 140 and is tuned to 800Hz by an LC filter. The second section, TR$_3$, TR$_4$, TR$_5$ and TR$_6$, has a gain of approximately 14 and is capable of amplifying linearly up to 45V peak-to-peak.

The output is capacitively coupled to transformer T$_1$ in the phase-sensitive rectifier.

REFERENCE SQUARE-WAVE GENERATOR

An 800Hz reference square-wave is generated by a 101CAYA electroluminescent diode and a BPX25 phototransistor mounted at the periphery of the radiation chopper disc (Fig. 4). The signal from the phototransistor is used to trigger a bistable circuit consisting of TR$_3$ and TR$_4$ which then drives the phase-sensitive rectifier transformer T$_2$ (Fig. 5) via the two emitter followers TR$_5$ and TR$_6$.

The relative phase between the signal and reference waveforms can be set by adjusting the position of the diode and phototransistor along the circumference of the chopper. Since the various detectors have differing response times and circuit configurations, the phase usually needs readjusting when the type of detector is varied. If required, a set of diodes and phototransistors, each pair corresponding to a particular type of detector, and switched into circuit with that detector, can be mounted at the chopper.

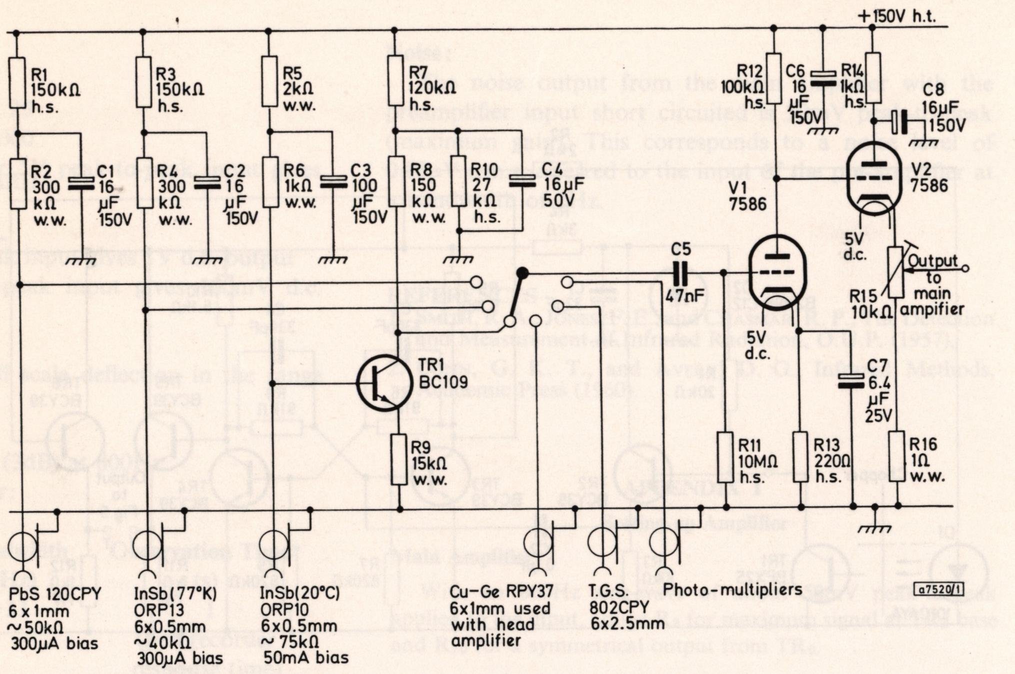

+150V h.t.
R1 150kΩ h.s.
R2 300 kΩ w.w.
C1 16 μF 150V
R3 150kΩ h.s.
R4 300 kΩ w.w.
C2 16 μF 150V
R5 2kΩ w.w.
R6 1kΩ w.w.
C3 100 μF 150V
R7 120kΩ h.s.
R8 150 kΩ w.w.
R10 27 kΩ h.s.
C4 16μF 50V
R12 100kΩ h.s.
C6 16 μF 150V
R14 1kΩ h.s.
C8 16μF 150V
V1 7586
V2 7586
5V d.c.
C5 47nF
R15 10kΩ
Output to main amplifier
5V d.c.
C7 6.4 μF 25V
TR1 BC109
R9 15kΩ w.w.
R11 10MΩ h.s.
R13 220Ω h.s.
R16 1Ω w.w.
PbS 120CPY 6×1mm ~50kΩ 300μA bias
InSb(77°K) ORP13 6×0.5mm ~40kΩ 300μA bias
InSb(20°C) ORP10 6×0.5mm ~75kΩ 50mA bias
Cu-Ge RPY37 6×1mm used with head amplifier
T.G.S. 802CPY 6×2.5mm
Photo-multipliers
a7520/1

Fig. 2—Preamplifier

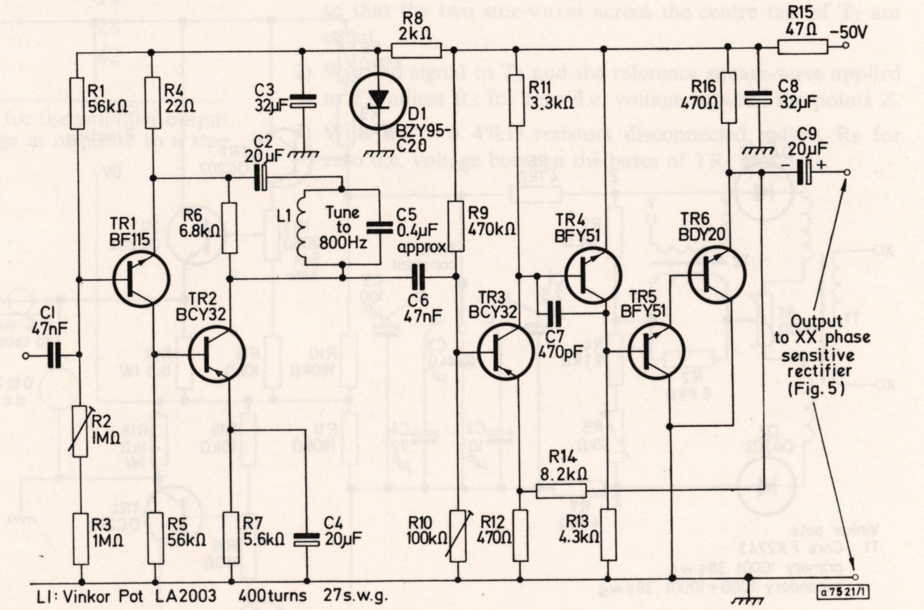

R8 2kΩ
R15 47Ω -50V
R1 56kΩ
R4 22Ω
C3 32μF
D1 BZY95-C20
R11 3.3kΩ
R16 470Ω
C8 32μF
C2 20μF
C9 20μF
L1
Tune to 800Hz
C5 0.4μF approx
R6 6.8kΩ
R9 470kΩ
TR1 BF115
TR2 BCY32
C6 47nF
TR3 BCY32
TR4 BFY51
C7 470pF
TR5 BFY51
TR6 BDY20
Output to XX phase sensitive rectifier (Fig.5)
C1 47nF
R2 1MΩ
R14 8.2kΩ
R3 1MΩ
R5 56kΩ
R7 5.6kΩ
C4 20μF
R10 100kΩ
R12 470Ω
R13 4.3kΩ
L1: Vinkor Pot LA2003 400turns 27s.w.g.
a7521/1

Fig. 3—Main amplifier

PHASE-SENSITIVE RECTIFIER

The principles of phase-sensitive rectification have been described in several texts (for example, see Ref. 2) where it is shown that a phase-sensitive rectifier improves the signal-to-noise ratio of an amplifier by the ratio

$$\frac{\text{Noise}_{\text{phase-sensitive rect.}}}{\text{Noise}_{\text{amplifier}}}=\left(\frac{\Delta f_{\text{phase-sensitive rect.}}}{\Delta f_{\text{amplifier}}}\right)^{\frac{1}{2}},$$

where Δf = bandwidth.

The bandwidth of a phase-sensitive rectifier followed by a simple RC low-pass filter is given by

$$\Delta f=\frac{1}{4RC}=\frac{1}{4t}$$

where R = resistance of filter
C = capacitance of filter
t = time-constant of filter.

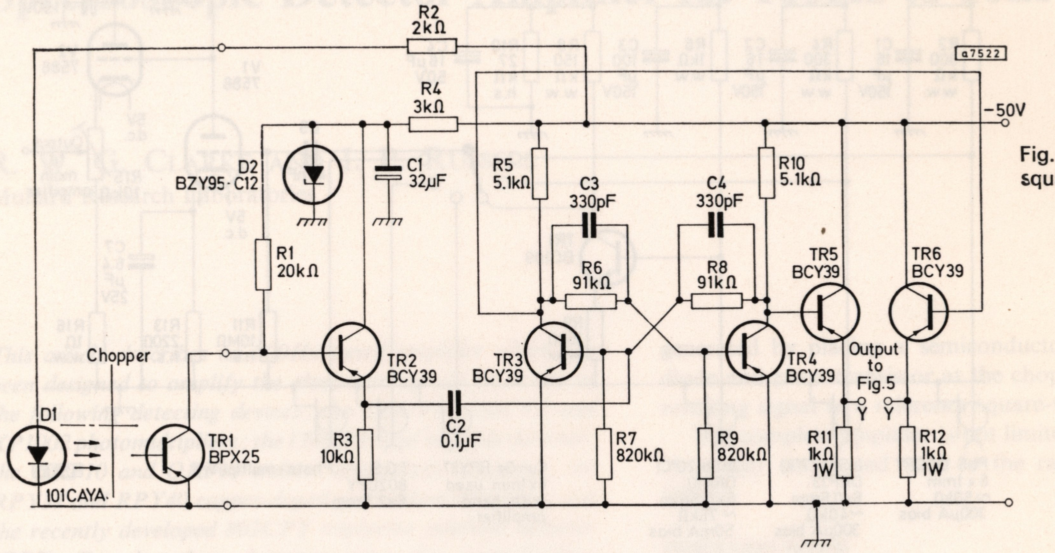
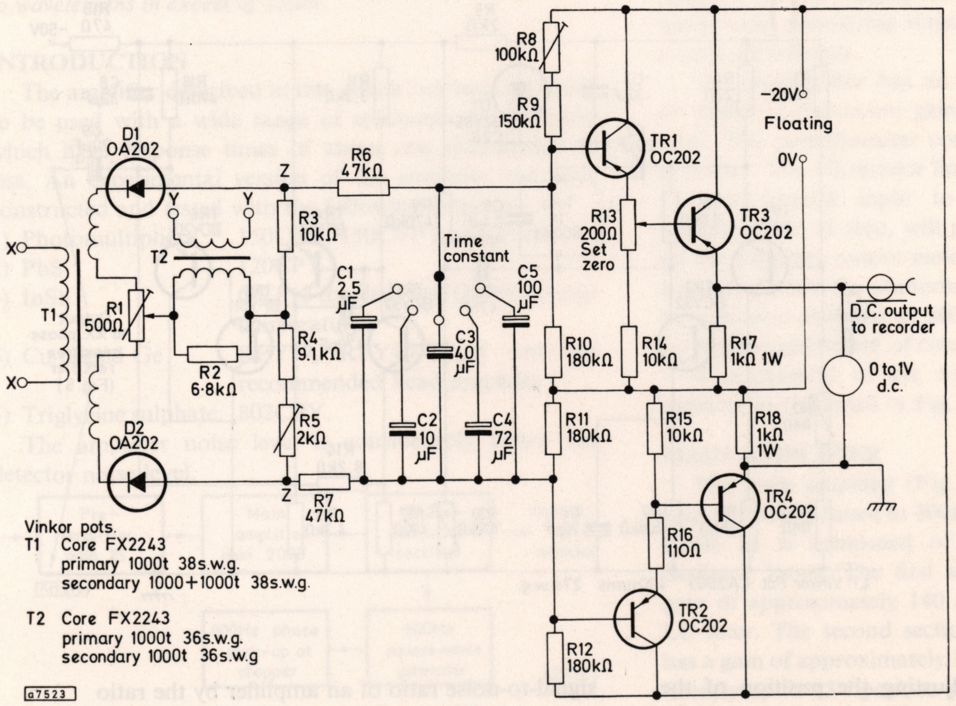

R2
2kΩ
a7522
R4
3kΩ
−50V
D2
BZY95-C12
C1
32μF
R5
5.1kΩ
C3
330pF
C4
330pF
R10
5.1kΩ
R1
20kΩ
R6
91kΩ
R8
91kΩ
TR5
BCY39
TR6
BCY39
Chopper
TR2
BCY39
TR3
BCY39
TR4
BCY39
Output
to
Fig.5
Y
Y
D1
C2
0.1μF
TR1
BPX25
R3
10kΩ
R7
820kΩ
R9
820kΩ
R11
1kΩ
1W
R12
1kΩ
1W
101CAYA

Fig. 4—Reference square-wave generator


R8
100kΩ
−20V
Floating
R9
150kΩ
TR1
OC202
0V
D1
OA202
Z
R6
47kΩ
Y
Y
R3
10kΩ
R13
200Ω
Set
zero
TR3
OC202
X
T2
Time
constant
C1
2.5
μF
C5
100
μF
T1
R1
500Ω
D.C. output
to recorder
R4
9.1kΩ
C3
40
μF
R2
6·8kΩ
R10
180kΩ
R14
10kΩ
R17
1kΩ 1W
0 to 1V
d.c.
X
R5
2kΩ
C2
10
μF
C4
72
μF
R11
180kΩ
R15
10kΩ
R18
1kΩ
1W
D2
OA202
Z
R7
47kΩ
TR4
OC202
R16
110Ω
TR2
OC202
R12
180kΩ
a7523

Vinkor pots.
T1 Core FX2243
primary 1000t 38s.w.g.
secondary 1000+1000t 38s.w.g.

T2 Core FX2243
primary 1000t 36s.w.g.
secondary 1000t 36s.w.g

Fig. 5—Phase-sensitive rectifier

The bandwidth of the phase-sensitive rectifier can easily be made very small (for example, 0·014Hz) and since the bandwidth of the amplifier is 140Hz, the overall noise is, in this example, reduced by a factor of one hundred. An important corollary of this result is that when there is say 0·04V noise (full scale deflection signal 1V) in the output of the phase-sensitive rectifier (bandwidth 0·014Hz), the amplitude of the noise from the amplifier is four times the amplitude of the signal. For this reason the main amplifier was designed to have an output capable of amplifying linearly up to 45V peak-to-peak.

In the circuit shown in Fig. 5 the signal is phase-sensitive rectified by using the reference square-wave to open and close a gate formed by D_1 and D_2. If this operation is performed in phase with the signal, a d.c. voltage proportional to the signal voltage is applied to the bases of the first pair of transistors TR_1 and TR_2. These drive the output transistors TR_3 and TR_4. The d.c. signal output voltage, which appears at the emitters of TR_3 and TR_4, is between 100mV and 1V d.c. for a full scale deflection and can supply 3mA to drive a pen recorder.

The emitter resistors of TR_2 and TR_3 provide a d.c. set-zero control and the switched capacitors give a range of time-constants.

PERFORMANCE

Gain:

(i) Preamplifier 25
(ii) Main amplifier 2000
(iii) Phase-sensitive rectifier 5V peak-to-peak input gives 1V d.c. output

Sensitivity:

Minimum 1V peak-to-peak input gives 1V d.c. output
Maximum 10μV peak-to-peak input gives 100mV d.c. output

Linearity:

Better than 1% with a full scale deflection in the range from 100mV to 5V d.c.

Bandwidth:

(i) Main amplifier 140Hz (3dB) at 800Hz
(ii) Phase-sensitive rectifier:

Time-constant Switch Position	Bandwidth (Hz)	Observation Time* (s)
1	0·33	1 (pen recorder response time)
2	0·25	4
3	0·07	14
4	0·036	28
5	0·02	42

*The observation time is the time taken for the amplifier output to reach 99% of the final output voltage in response to a step voltage at the input.

Noise:

The noise output from the main amplifier with the preamplifier input short circuited is 30mV peak-to-peak (maximum gain). This corresponds to a noise level of 0·05μV r.m.s. referred to the input of the pre-amplifier at a bandwidth of 1Hz.

REFERENCES

1. Smith, R. A., Jones, F. E., and Chasmar, R. P., The Detection and Measurement of Infrared Radiation, O.U.P. (1957).
2. Conn, G. K. T., and Avery, D. G., Infrared Methods, Academic Press (1960).

APPENDIX 1

Setting-up Amplifier

Main Amplifier

With an 800Hz sine-wave of about 50mV peak-to-peak applied to the input, adjust R_2 for maximum signal at TR_3 base and R_{10} for a symmetrical output from TR_6.

Phase-sensitive Rectifier

1) With an 800Hz signal of about 1V applied to T_1 adjust R_1 so that the two sine-waves across the centre tap of T_1 are equal.
2) With no signal to T_1 and the reference square-wave applied to T_2, adjust R_5 for zero d.c. voltage between the points Z.
3) With the two 47kΩ resistors disconnected, adjust R_8 for zero d.c. voltage between the bases of TR_1 and TR_2.

Single System I.F. Amplifier for U.K. 625-line System

P. Bissmire
Mullard Central Application Laboratory

This article describes a high gain four transistor i.f. amplifier suitable for colour or monochrome reception. The middle stage consists of cascode connected BF197 and BF194 transistors, resulting in a high degree of stability. The amplifier offers the advantage of simple alignment. A full practical circuit is given.

INTRODUCTION

The advent of colour television and of u.h.f. single standard operation necessitate a re-examination of the design philosophy for television i.f. amplifiers. This article examines the implications of the new conditions of operation and arrives at a specification for a suitable amplifier. A practical design is presented, based on this specification.

DETECTION OF A COMPATIBLE COLOUR SIGNAL

The PAL system composite signal contains three major frequency components. Referred to the standard intermediate frequencies these are

vision carrier	39·5MHz,
chrominance	35·066MHz,
sound carrier	33·5MHz.

In addition it will be noticed that the chrominance information is impressed on the vision carrier as single sideband modulation, since it lies outside the vestigial sideband region.

The distortion inherent in processing this information in an envelope detector must be investigated, and means sought of reducing it to a minimum.

Sound-chroma Beat

The possible detection products may be tabulated as follows:

luminance	0 to 5·5MHz wanted
chrominance	4·434MHz wanted
sound intercarrier	6·0MHz wanted
sound-chroma beat	1·566MHz unwanted

It is usual practice to attenuate the sound carrier by some 26dB before detection, thus the sound-chroma beat will be at a low amplitude. However, the sound carrier is frequency modulated and consequently the 1·566MHz pattern which appears on the screen will twist and break up in step with the sound modulation, thus rendering its visibility and annoyance value very high. Since the unwanted beat lies within the luminance band, it cannot be removed after detection without severe modification of the luminance response. We must, therefore, consider heavy attenuation of one or other of the frequencies giving rise to the beat frequency, prior to detection. Attenuation of the chrominance would give rise to restricted luminance bandwidth, since it lies within the upper limit of the luminance band. We are thus restricted to further attenuation of the sound carrier. It is found that an attenuation greater than 36dB is required to reduce the sound-chroma beat to an acceptable level. If only one detector is used to recover all the information, a very high gain sound i.f. will be required. A more acceptable solution is to include a part of the sound trapping at the input to the luminance detector, and use a second detector to recover the intercarrier sound at a more normal level.

A choice of detectors is now available for recovery of the chrominance signal. At the luminance detector the output is free from sound-chroma beat, but, as a result of the heavy sound trapping, the chroma signal will lie in the region of a steep response skirt and large variations of group delay. At the sound detector the response excursions will be more acceptable, and, since it lies well outside the wanted band, the sound-chroma beat can be rejected by simple filtering after detection.

Envelope Distortion

A form of distortion often occurs in the reception of a compatible colour signal, in which the bright and highly saturated areas of the picture suffer a loss of brightness and saturation. This corresponds to areas of low envelope amplitude with a high level of superimposed chrominance modulation. This distortion has two separate causes.

1) A practical envelope detector, using a diode, has a non-linear "bottom-bend". In the picture areas described, the chrominance signal will be partially detected in this region, giving a reduced chrominance output and a rectified chrominance contribution to the luminance signal. This is shown in Fig. 1.
2) The chrominance information is transmitted as modulation of one sideband only of the vision signal. Fig. 2 shows the envelope of this modulation, from which it can be seen that once again the chrominance output is reduced and a rectified chrominance component added to the luminance signal. Fig. 3 shows the relationship between this effect and the relative levels of chrominance and luminance signals.

This distortion may be reduced by adjusting the relative levels of chrominance and vision carrier prior to detection. (For a detailed discussion of this type of distortion see Ref. 1.) Fig. 4a shows the idealised response shapes chosen to do this. Since the number of tuned circuits in the amplifier is limited, a practical response will be as shown in Fig. 4b.

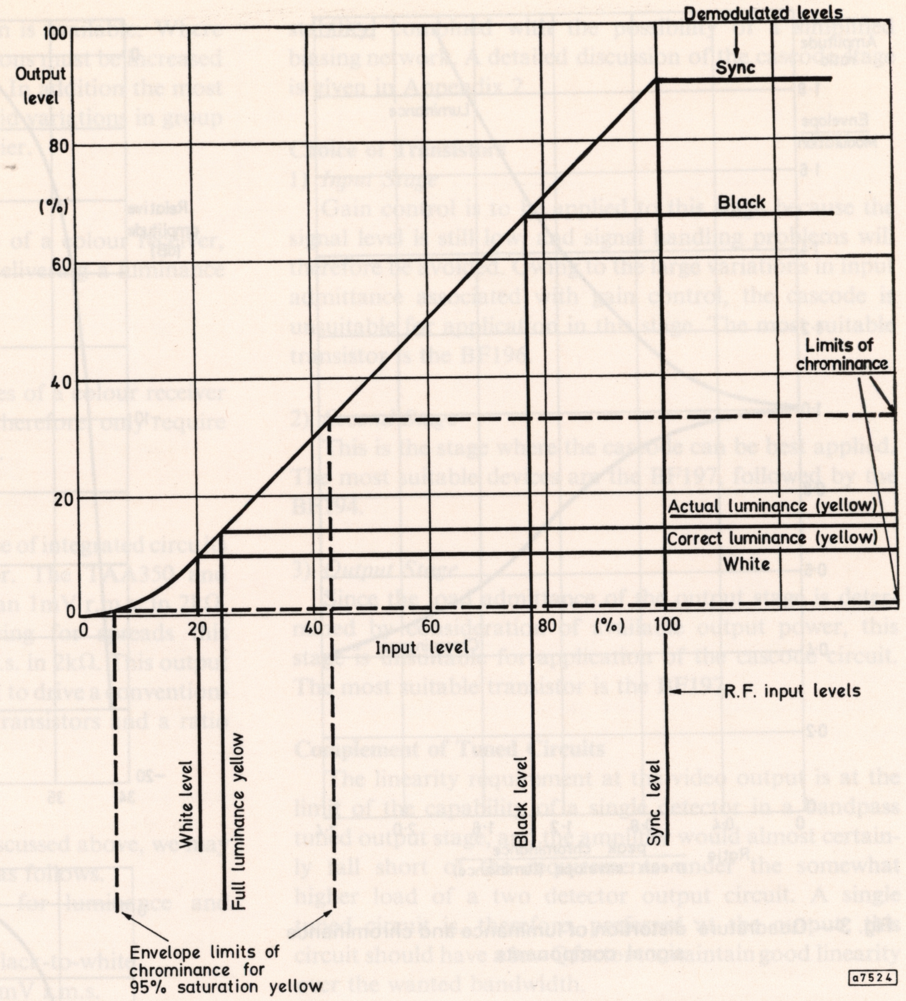


Fig. 1—Distortion of 95% saturated full amplitude yellow by detector bottom end

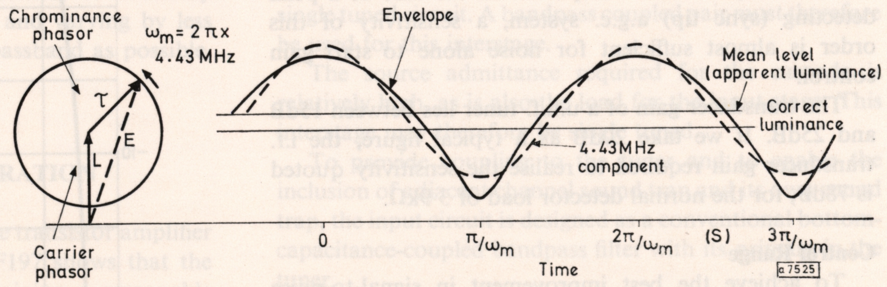


Fig. 2—Envelope of 95% saturated full amplitude yellow

REQUIREMENTS IMPOSED BY U.H.F. SINGLE STANDARD OPERATION

In a dual standard receiver the v.h.f. tuner has a fairly high gain, and its mixer is usually used as an i.f. amplifier for the u.h.f. tuner, to equalise the signals fed to the main i.f. amplifier. A single standard receiver will be equipped with a relatively low gain u.h.f. tuner only. This modifies the requirements for gain and control range.

Gain

For definitions of the gains referred to in this article see Appendix 1.

An upper limit on receiver gain is imposed by signal-to-noise ratio requirements. A maximum sensitivity of 17μV e.m.f. in 75Ω for 2V d.c. in the detector load gives a minimum signal-to-noise ratio of 15dB at full gain, for a tuner noise figure of 8dB. A signal-to-noise ratio of this order

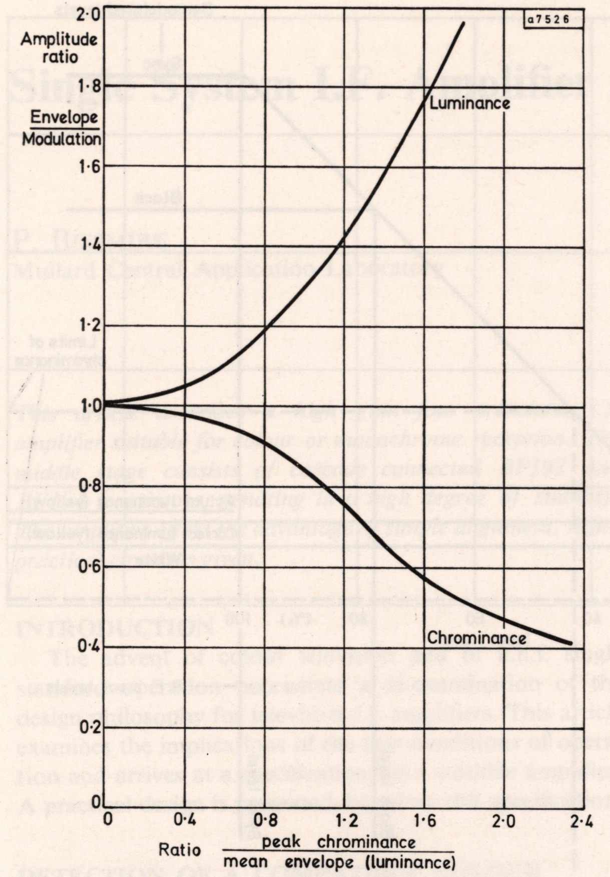


Fig. 3—'Quadrature' distortion of luminance and chrominance signal components

yields an intelligible picture, but of minimal entertainment value. However, it is necessary to ensure that the a.g.c. system will be operative under the worst conditions that any user may consider acceptable. In the case of a peak detecting (sync tip) a.g.c. system, a sensitivity of this order is almost sufficient for noise alone to start gain control.

The transducer gain of a u.h.f. tuner lies between 15dB and 25dB. If we take 20dB as a typical figure, the i.f. transducer gain required to realise the sensitivity quoted is 78dB, for the normal detector load of 3·9kΩ.

Control Range

To achieve the best improvement in signal-to-noise ratio with reduction in gain, the maximum amount of control must be applied to the i.f. amplifier before the start of tuner control. The upper limit to the useful control range in the i.f. amplifier is set by the occurrence of overloading of the mixer stage. Typically this will occur when the i.f. gain falls below about 33dB. Thus for the gain quoted above the amplifier should have a control range somewhat greater than 45dB.

OTHER REQUIREMENTS

Group Delay

Subjective assessment has shown that, for a 625 line, 25 f.p.s. signal, group delay variations of 30ns are just discernible when a direct comparison is available. Where no comparison is available the variations must be increased to 60ns to render their effects visible. In addition the most annoying effects are produced by rapid variations in group delay in the region of the vision carrier.

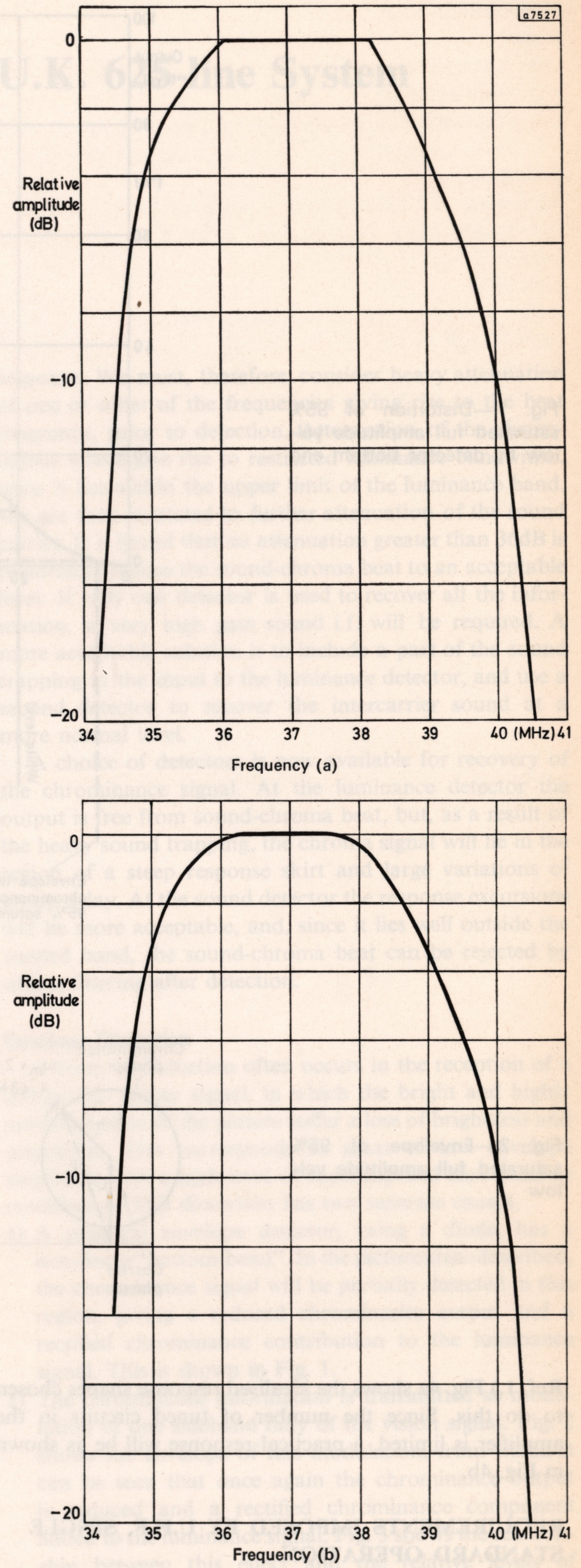


Fig. 4*(a)*—Proposed response (ideal form) at collector of output stage
(b)—Proposed response (practical form) at collector of output stage

Luminance Output

To satisfy the drive requirements of a colour receiver, the amplifier should be capable of delivering a luminance output of 3·5 to 4V black-to-white.

Chrominance Output

The chrominance processing stages of a colour receiver usually have a fairly high gain and, therefore, only require an input of the order of 10mV r.m.s.

Sound Output

The present trend is towards the use of integrated circuits for the intercarrier sound amplifier. The TAA350 and TAA570 require an input greater than 1mV r.m.s. in 2kΩ, for good a.m. suppression. Allowing for spreads this indicates a nominal level of 3mV r.m.s. in 2kΩ. This output should also be a sufficient power level to drive a conventional sound section consisting of two transistors and a ratio detector.

SPECIFICATIONS

Summarising the requirements discussed above, we may specify the amplifier characteristics as follows.

Detection: separate detectors for luminance and sound-chrominance
Luminance output: 3·5 to 4V black-to-white
Chrominance output: about 10mV r.m.s.
Sound i.f. output: 3mV r.m.s.
Amplitude-frequency response: within passband substantially as shown in Fig. 4.
Group delay frequency characteristics: substantially flat in the region of the carrier, and varying by less than 60ns over as much of the passband as possible.
Gain: 78dB
Control range: 45dB

CHOICE OF CIRCUIT CONFIGURATION

Number of Transistors

A theoretical examination of a three transistor amplifier using transistor types BF196 and BF197 shows that the maximum gain obtainable, while retaining a reasonable margin of stability, is about 65dB, some 13dB lower than specified above. The extra gain can only be achieved by the addition of a fourth transistor if a sacrifice of stability and ease of alignment is to be avoided.

Cascode Stage

The required selectivity can readily be obtained in a three stage amplifier, but the required gain is considerably lower than that which could be achieved in a four stage design. It is, therefore, desirable to choose a method of interconnecting two transistors in a single stage. The cascode configuration has been chosen as offering the greatest ease of obtaining high gain with a large margin of stability, combined with the possibility of a simplified biasing network. A detailed discussion of the cascode stage is given in Appendix 2.

Choice of Transistors

1) *Input Stage*

Gain control is to be applied to this stage because the signal level is still low, and signal handling problems will therefore be avoided. Owing to the large variations in input admittance associated with gain control, the cascode is unsuitable for application in this stage. The most suitable transistor is the BF196.

2) *Second Stage*

This is the stage where the cascode can be best applied. The most suitable devices are the BF197, followed by the BF194.

3) *Output Stage*

Since the load admittance of the output stage is determined by consideration of available output power, this stage is unsuitable for application of the cascode circuit. The most suitable transistor is the BF197.

Complement of Tuned Circuits

The linearity requirement at the video output is at the limit of the capability of a single detector in a bandpass tuned output stage, and the amplifier would almost certainly fall short of the requirements under the somewhat higher load of a two detector output circuit. A single tuned circuit is, therefore, preferred at the output; this circuit should have a low Q factor to maintain good linearity over the wanted bandwidth.

The output stage needs to be fed from a high source admittance while the cascode requires a low load admittance. At the level of Q needed for adequate bandwidth, it is impossible to realise this high admittance ratio from a single tuned circuit. A bandpass coupled pair must therefore be used for this interstage.

The source admittance required for the cascode is relatively high, as is also the load for the input stage. This interstage may therefore be single tuned.

To provide coupling to the tuner and to enable the inclusion of adjacent channel sound trap and its own sound trap, the input circuit is designed as a conventional bottom-capacitance-coupled bandpass filter with its primary in the tuner.

The tuned circuit configuration is thus two cascaded triplets, each consisting of a coupled pair followed by a single tuned circuit.

PRACTICAL CIRCUIT

Fig. 5 shows the basic amplifier in diagrammatic form. The isolated working Q factor of each tuned circuit is shown, including any transistor damping and also the total conductance at its input or output terminals as appropriate. In addition the coupling factor of coupled pairs is indicated, together with their overall Q factors. Also shown are the stage gains and signal levels through the amplifier.

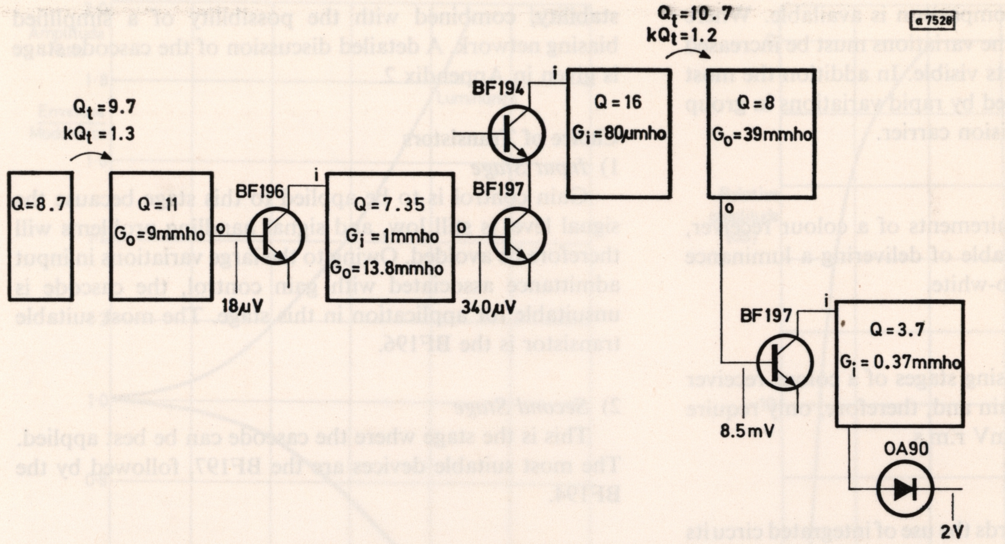

Q=8.7
Q_t=9.7
kQ_t=1.3
Q=11
G_o=9mmho
BF196
18μV
Q=7.35
G_i=1mmho
G_o=13.8mmho
BF194
BF197
340μV
Q=16
G_i=80μmho
Q_t=10.7
kQ_t=1.2
Q=8
G_o=39mmho
BF197
Q=3.7
G_i=0.37mmho
8.5mV
OA90
2V
α 7528

Fig. 5—Circuit constants

The isolated stability factors of the input and output stages are in excess of six, giving sensibly independent behaviour of the input and output tuned circuits of these stages during alignment. The major contribution to feedback in the cascode stage is from layout strays. Nevertheless, for a reasonably well designed printed board, without extra screening, the stage stability should still be in excess of 10. This high stability of the centre stage effectively isolates the input and output stages, virtually eliminating any degradation of stage stability factors by cascading.

Fig. 6 shows the complete circuit diagram of the amplifier with input traps, TAA350 sound amplifier and detector luminance and chrominance pre-stages and a.f.c. discriminator. An outline of the design procedure used for each stage is given in Appendix 3.

D.C. Conditions

The amplifier as shown operates from a +20V supply rail, but may be modified to operate from any rail voltage between 20V and 30V of either polarity. The d.c. conditions in the transistors should be maintained as follows:

	BF196*	BF197	BF194	BF197
V_{CE} (V)	10	8	—	16·5
I_e (mA)	4	7	7	7

* without gain control

The collector dissipations allow an adequate margin of safety for operation at 55°C.

Application of A.G.C.

To conform to the requirements of a particular a.g.c. system the biasing circuit of the BF196 may be modified provided the d.c. conditions indicated above are maintained. The d.c. resistance in series with the transistor should be maintained at about 1kΩ or higher to reduce response shape distortion and give the best obtainable signal-to-noise ratio improvement with control.

First Luminance Splitter

The detector gives a positive going output which is directly coupled to the base of the BF194 luminance pre-stage. This stage, therefore, only requires sufficient bias to ensure that the transistor is still just conducting with no input signal. The circuit shown gives a quiescent current of about 0·4mA. This arrangement also gives a very small forward bias to the detector diode.

Input Traps

An own-sound trap, and a channel 1 and adjacent sound trap, are included as a part of the bottom coupling impedance at the input to the amplifier, the bottom capacitance itself being distributed equally on either side of the traps. The adjacent sound trap is resistance compensated to minimise its effects on the vestigial side-band response. The compensating resistor R_1 is shown as a fixed component, which appears to give sufficiently consistent compensation.

A third trap is included in the base coupling circuit of the BF196 to provide further attenuation of the adjacent vision carrier.

Output Transformer

A bifilar transformer is shown coupling the luminance detector to the output stage. If it is thought desirable, a simple coil may be used here instead, with choke-capacitance coupling. Some additional capacitance may be required across the coil, in this case, to adjust the Q factor.

The lower-Q tuned circuit feeding the sound-chrominance detector is loosely coupled to the output stage by a small tertiary winding.

Chrominance Pre-stage

To maintain a constant chrominance amplitude under poor propagation conditions, this stage is gain controlled. A BF194 operates in reverse control, the control voltage being derived from the burst phase detector in the decoder. (Ref. 2) The stage is fed from the sound-chrominance detector via an attenuator and high-pass filter, to reduce the sound-chrominance beat from the detector and maintain good signal handling. The bandwidth is further reduced by a low Q factor tuned circuit in the collector of the BF194, chiefly to improve the signal-to-noise ratio.

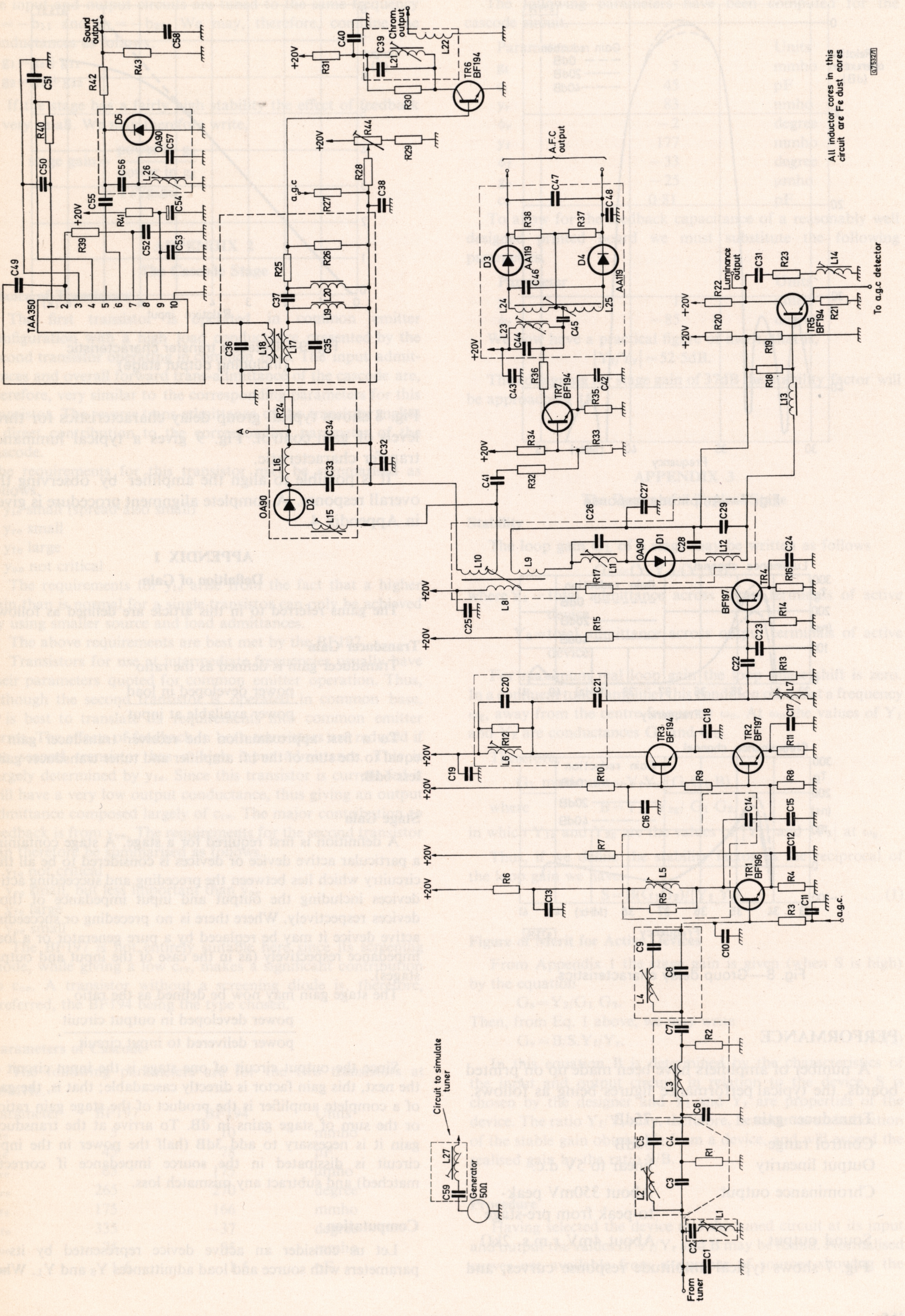

TAA350
Sound output
Chrom output
A.F.C output
Luminance output
To a.g.c detector
All inductor cores in this circuit are Fe dust cores
a.g.c
+20V
TR1 BF196
TR2 BF197
TR3 BF194
TR4 BF197
TR5 BF194
TR6 BF194
TR7 BF194
D1 OA90
D2 OA90
D3 AA119
D4 AA119
D5 OA90
Circuit to simulate tuner
Generator 50Ω
From tuner

Fig. 6—Complete i.f. amplifier

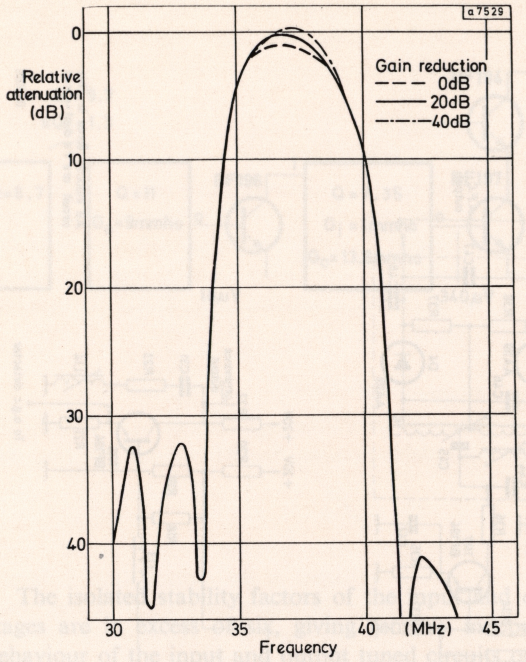


Fig. 7—Amplitude response

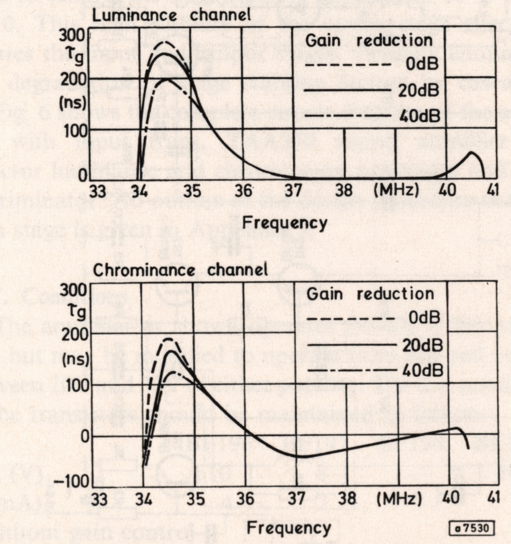


Fig. 8—Group delay characteristics

PERFORMANCE

A number of amplifiers have been made up on printed boards, the typical performance figures being as follows.

Transducer gain	75dB
Control range	50dB
Output linearity	linear to 5V d.c.
Chrominance output	About 350mV peak-to-peak from pre-stage
Sound output	About 4mV r.m.s. 2kΩ

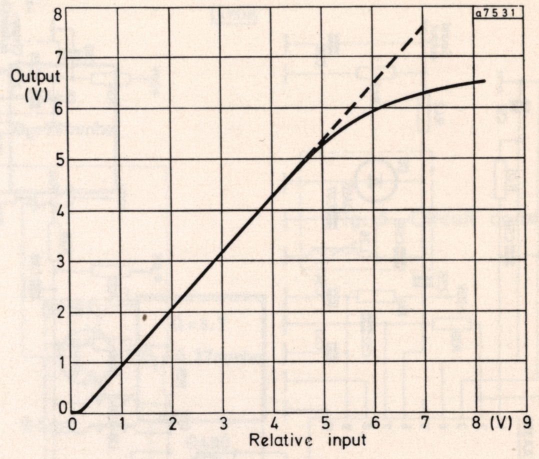


Fig. 9—Detector transfer characteristic (including output stage)

Fig. 7 shows typical amplitude response curves, and Fig. 8 shows typical group delay characteristics for three levels of gain control. Fig. 9 gives a typical luminance transfer characteristic.

It is possible to align the amplifier by observing the overall response. A complete alignment procedure is given in Appendix 4.

APPENDIX 1

Definition of Gain

The gains referred to in this article are defined as follows.

Transducer Gain

Transducer gain is defined as the ratio

$$\frac{\text{power developed in load}}{\text{power available at input}}.$$

To a first approximation the receiver transducer gain is equal to the sum of the i.f. amplifier and tuner transducer gains less 6dB.

Stage Gain

A definition is first required for a stage. A stage containing a particular active device or devices is considered to be all that circuitry which lies between the preceding and succeeding active devices including the output and input impedance of those devices respectively. Where there is no preceding or succeeding active device it may be replaced by a pure generator or a load impedance respectively (as in the case of the input and output stages).

The stage gain may now be defined as the ratio

$$\frac{\text{power developed in output circuit}}{\text{power delivered to input circuit}}.$$

Since the output circuit of one stage is the input circuit of the next, this gain factor is directly cascadable; that is, the gain of a complete amplifier is the product of the stage gain ratios, or the sum of stage gains in dB. To arrive at the transducer gain it is necessary to add 3dB (half the power in the input circuit is dissipated in the source impedance if correctly matched) and subtract any mismatch loss.

Computation

Let us consider an active device represented by its Y parameters with source and load admittances Y_S and Y_L. When the input and output circuits are tuned to the same frequency $b_s = -b_{11}$ and $b_L = -b_{22}$. We may, therefore, combine the conductances as follows:

$$g_1 = g_s + g_{11}$$
$$g_2 = g_L + g_{22}$$

If the stage has a fairly high stability the effect of feedback is very small. We may therefore write,

$$\text{stage gain} = \frac{\text{power in } g_2}{\text{power in } g_1} = Y_f^2/g_1 g_2.$$

APPENDIX 2

The Cascode Stage

Choice of Transistors

The first transistor is operated in common emitter configuration with a high load conductance presented by the second transistor operating in common base. The input admittances and overall forward trans-admittance of the cascode are, therefore, very similar to the corresponding parameters for this transistor. The reverse trans-admittance of the transistor makes a direct contribution to the corresponding parameter of the cascode.

The requirements for this transistor may be summarised as follows.

y_{ie} small (spread also small)
y_{re} small
y_{fe} large
y_{oe} not critical

The requirements for y_{ie} arise from the fact that a higher gain than is normal for a single transistor can only be achieved by using smaller source and load admittances.

The above requirements are best met by the BF197.

Transistors for use at intermediate frequencies usually have their parameters quoted for common emitter operation. Thus, although the second transistor is operated in common base, it is best to translate its requirements into common emitter terms. The effects of feedback in both transistors are reduced if the second transistor has a high input admittance. This is largely determined by y_{fe}. Since this transistor is current-fed it will have a very low output conductance, thus giving an output admittance composed largely of c_{re}. The major contribution to feedback is from y_{oe}. The requirements for the second transistor can therefore be summarised as follows.

y_{ie} not critical
y_{re} small, but less important than y_{oe}
y_{fe} large
y_{oe} small

The BF197 is not entirely suitable here since its screening diode, while giving a low c_{re}, makes a significant contribution to c_{oe}. A transistor without a screening diode is, therefore, preferred, the BF194 being the type chosen.

Parameters of Cascode

The following parameters are for the two transistors at 36MHz.

Parameter	BF197	BF194	Units
g_{ie}	5	10	mmho
c_{ie}	45	78	pF
y_{re}	65	175	μmho
ϕ_{re}	265	270	degree
y_{fe}	175	166	mmho
ϕ_{fe}	335	−37	degree
g_{oe}	75	85	mmho
c_{oe}	1·6	1·5	pF

The following parameters have been computed for the cascode circuit.

Parameter		Units
g_i	5	mmho
c_i	45	pF
y_r	83	nmho
ϕ_r	−2	degree
y_f	177	mmho
ϕ_f	−33	degree
g_o	−25	μmho
c_o	0·81	pF

To allow for the feedback capacitance of a reasonably well designed printed board we must substitute the following parameters.

Parameter		Units
y_r	1	μmho
ϕ_r	−85	degree

We now have a practical figure of merit, that is,

$$|Y_f/Y_r| = 52{\cdot}5\text{dB}.$$

Thus designing for stage gain of 37dB the stability factor will be approaching 15.

APPENDIX 3

The Design of a Typical Stage

Stability

The loop gain G_L of a stage may be written as follows

$$G_L = (Y_f Y_r)/(Y_1 Y_2),$$

where Y_1 = total admittance across input terminals of active device.
Y_2 = total admittance across output terminals of active device.

For maximum real loop gain the loop phase shift is zero. In a confluent tuned amplifier this condition occurs at a frequency ω_g, away from the centre frequency ω_o. At ω_o the values of Y_1 and Y_2 are conductances G_1 and G_2.

Therefore,

$$G_L \text{ maximum} = Y_f Y_r/(G_1 G_2.B),$$

where $B = Y_{1g}\, Y_{2g}/\, G_1\, G_2$,

in which Y_{1g} and Y_{2g} are the values of $|Y_1|$ and $|Y_2|$ at ω_g.

Thus, if we define the stability factor as the reciprocal of the loop gain we have,

$$S = B(G_1 G_2)/|Y_f\, Y_r|. \qquad \ldots(1)$$

Figure of Merit for Active Devices

From Appendix 1 the stage gain is given (when S is high) by the equation

$$G_s = Y_2/G_1\, G_2.$$

Then, from Eq. 1 above, we may write

$$G_s = B/S.Y_f/Y_r. \qquad \ldots(2)$$

In this equation B is determined by the characteristics of the input and output circuits in relation to the device, S is chosen by the designer and Y_f and Y_r are properties of the device. The ratio Y_f/Y_r may, therefore, be taken as an indication of the stable gain obtainable from a device, and will exceed the realised gain by the ratio S/B.

Procedure

Having selected the device and the tuned circuit at its input and output the values of Y_f/Y_r and B may be found. Normalised curves are available from a number of sources showing the variations of input admittance with frequency of various types of band-pass filter. From these the value of B for the filters chosen can be derived. Choosing a value for S, the stage gain may be found from Eq. 2, and $G_1 G_2$ from the equation

$$G_1 G_2 = Y_f^2/G_s. \qquad \ldots(3)$$

It now remains to choose values for G_1 and G_2. In some cases, as in the output stage, where the output must be power matched, one of these is fixed; otherwise the choice must be made on the basis of convenience and the best masking of spreads in the input and output parameters of the device.

APPENDIX 4

Alignment Procedure

1) The following procedure is used in the laboratory. Connect a 50Ω wobbulator to the amplifier input using the simulated tuner circuit shown. Observe the response at the luminance output. Adjust the gain of the amplifier to about 20dB below maximum and the display sensitivity for 4V at full scale. Throughout the adjustments maintain the response peak at about full scale by adjusting the input level. The main amplifier may then be aligned as follows

Adjust	For	At
L_1	minimum	33·7MHz
L_2	minimum	41·5MHz
L_4	minimum	31·5MHz
L_{11}	minimum	33·5MHz
L_5	maximum	36·5MHz
L_8	maximum	36·5MHz
tuner circuit	maximum	35·0MHz
L_3	maximum	39·5MHz
L_6	−5½ to −6dB	39·5MHz
L_7	correct tilt	

2) Observe the response at point "A" (Fig. 6) re-adjusting the gain of the display unit for an acceptable display.

Adjust	For	At
L_{15}	maximum	39·5MHz

3) Still maintaining the same input level, observe the response at the a.f.c. output. Withdraw the core from L_{24} and L_{25}. Take care not to screw the cores in too far and overcouple the discriminator transformer, and

adjust	for	at
L_{23}	maximum	39·5MHz
L_{24} and L_{25}	zero crossing	39·5MHz.

4) The tuner simulating circuit should now be removed, and the tuner, with the correct amount of damping across its i.f. output circuit to achieve the Q factor indicated in Fig. 5, should be connected in its place. The wobbulator signal must now be loosely capacitively coupled to the i.f. tuned circuit in the tuner and the response observed at the video output. Adjust the tuner circuit, L_3 and C_1 (C_1 by substitution) to obtain a response substantially as in step 1. Any slight residual tilt or error in carrier level (39·5MHz) may be corrected by small re-adjustments of L_6 and L_7.

5) Adjustments to the chrominance and sound circuits are simplest when the receiver is more or less complete. With the receiver tuned to a composite signal,

Adjust	For
L_{21}	maximum chrominance output
L_{14}	minimum chrominance content in the video output
L_{17}, L_{18} and L_{26}	maximum sound output with minimum distortion and video noise.

REFERENCES

1. ACHTERBERG, H., JUHNKE, K., SCHILLHOF, U., 'Der Einfluss der ZF-Verstärker-Durchlasskurve auf die Bildqualität eines Farbfernsehempfängers', **Valvo Berichte**, Vol. XIII, No. 1, July 1967, pp. 1 to 22.
2. HOBBS, D. S., 'Hybrid Colour-difference Decoding Circuits', **Mullard Technical Communications,** Vol. 9, No. 85, January 1967, pp. 111 to 118.

COMPONENTS

Resistors

All resistors are Mullard style CR25, from the group B803104NB

R_1	270Ω
R_2	3·3kΩ
R_3	470Ω
R_4	390Ω
R_5	1·5kΩ
R_6	820Ω
R_7	1·2kΩ
R_8	4·7kΩ
R_9	6·8kΩ
R_{10}	6·8kΩ
R_{11}	560Ω
R_{12}	10kΩ
R_{13}	820Ω
R_{14}	2·2kΩ
R_{15}	8·2kΩ
R_{16}	470Ω
R_{17}	100Ω
R_{18}	3·9kΩ
R_{19}	1kΩ
R_{20}	18kΩ
R_{21}	470Ω
R_{22}	1kΩ
R_{23}	390Ω
R_{24}	3·9kΩ
R_{25}	120Ω
R_{26}	56Ω
R_{27}	390kΩ
R_{28}	220kΩ
R_{29}	47kΩ
R_{30}	1kΩ
R_{31}	1·5kΩ
R_{32}	220Ω
R_{33}	4·7kΩ
R_{34}	5·6kΩ
R_{35}	1·2kΩ
R_{36}	100Ω
R_{37}	100kΩ
R_{38}	100kΩ
R_{39}	5·6kΩ
R_{40}	5·6kΩ
R_{41}	680Ω
R_{42}	3·3kΩ
R_{43}	10kΩ
R_{44}	100kΩ

Capacitors

C_1	120pF	C333CH/C120E
C_2	33pF	C333CC/C33E
C_3	150pF	C333CH/C150E
C_4	150pF	C333CH/C150E
C_5	39pF	C333CC/C39E
C_6	120pF	C333CH/C120E
C_7	33pF	C333CC/C33E
C_8	220pF	C333CH/C220E
C_9	22pF	C333CC/C22E
C_{10}	120pF	C333CH/C120E
C_{11}	2·2nF	
C_{12}	2·2nF	
C_{13}	2·2nF	
C_{14}	33pF	C333CC/C33E
C_{15}	56pF	C333CH/C56E
C_{16}	2·2nF	
C_{17}	2·2nF	
C_{18}	8·2pF	C333CB/N8E2
C_{19}	2·2nF	
C_{20}	2·7pF	C333CB/N2E7
C_{21}	2·2pF	C333CB/N2E2
C_{22}	47pF	C333CC/C47E
C_{23}	120pF	C333CH/C120E
C_{24}	2·2nF	
C_{25}	2·2nF	
C_{26}	47pF	C333CC/C47E
C_{27}	2·2nF	
C_{28}	5·6pF	C333CB/N5E6
C_{29}	6·8pF	C333CB/N6E8
C_{30}	Component deleted	
C_{31}	10pF	C333CB/N10E
C_{32}	2·2nF	
C_{33}	5·6pF	C333CB/N5E6
C_{34}	3·9pF	C333CB/N3E9
C_{35}	180pF	C333CH/C180E
C_{36}	220pF	C333CH/C220E
C_{37}	180pF	C333CH/C180E
C_{38}	100nF	C280AE/P100K
C_{39}	68pF	C333CH/C68E
C_{40}	47nF	C280AE/P47K
C_{41}	1nF	
C_{42}	2·2nF	
C_{43}	2·2nF	
C_{44}	27pF	C333CC/C27E
C_{45}	120pF	C333CH/C120E
C_{46}	15pF	C333CB/C15E
C_{47}	2·2nF	
C_{48}	2·2nF	
C_{49}	100nF	C280AE/P100K
C_{50}	100nF	C280AE/P100K
C_{51}	100nF	C280AE/P100K
C_{52}	100nF	C280AE/P100K
C_{53}	100nF	C280AE/P100K
C_{54}	50μF	C426AR/C50
C_{55}	39pF	C333CC/C39E
C_{56}	56pF	C333CH/C56E
C_{57}	150pF	C333CH/C150E
C_{58}	22nF	C280AE/P22K

Inductors

	Note	Former	Core	Wire	Number of Turns
L_1		P1011/1	4×0·5×6mm	38 s.w.g. t.n.a.	10
L_2		P1011/1	4×0·5×6mm	38 s.w.g. t.n.a.	8
L_3		P1011/1	4×0·5×6mm	38 s.w.g. t.n.a.	11
L_4		P1011/1	4×0·5×6mm	38 s.w.g. t.n.a.	15
L_5		P1011/1	4×0·5×6mm	38 s.w.g. t.n.a.	9
L_6		P1011/1	4×0·5×6mm	38 s.w.g. t.n.a.	27
L_7		P1011/1	4×0·5×6mm	38 s.w.g. t.n.a.	7
L_8	(1)	P1003/1	4×0·5×6mm	40 s.w.g. en.cu.	25
L_9				40 s.w.g. en.cu.	25
L_{10}				40 s.w.g. en.cu.	3
L_{11}				28 s.w.g. t.n.a.	9
L_{12}	(2)		CH2/1	47 s.w.g. en.cu.	86
L_{13}	(2)		FX1242	38 s.w.g. en.cu.	10
L_{14}	(3)	P1011/1	4×0·5×6mm	42 s.w.g. t.n.a.	140
L_{15}		P1003/1	4×0·5×12·7mm	40 s.w.g. en.cu.	30
L_{16}	(2)		CH2/1	47 s.w.g. en.cu.	86
L_{17}	(4)	P1003/1	4×0·5×6mm	42 s.w.g. t.n.a.	30
L_{18}					27
L_{19}	(2)		FX1242	38 s.w.g. en.cu.	6
L_{20}	(2)		FX1242	38 s.w.g. en.cu.	6
L_{21}	(5)	P1011/1	4×0·5×6mm	42 s.w.g. t.n.a.	50
L_{22}					25
L_{23}	(6)	P1003/1	4×0·5×6mm	38 s.w.g. en.cu.	7
L_{24}				42 s.w.g. en.cu.	6
L_{25}				42 s.w.g. en.cu.	6
L_{26}		P1011/1	4×0·5×6mm	42 s.w.g. t.n.a.	35
L_{27}		P1011/1	4×0·5×6mm	38 s.w.g. t.n.a.	20

Formers

P1011/1 and P1003/1 are E.I.H. Electronics Limited 3/16×3/4in and 3/16×1½in respectively.

Cores

FX1242 are Mullard ferrite pot cores, CH2/1 are Neosid choke cores. All others are Neosid grade 900.

Notes

(1) L_8 and L_9 are close bifilar wound at the bottom of the former, with L_{10} overwound at the earthy end. The core is inserted from the hot end. L_{11} is wound at the top of the former.

(2) L_{12} and L_{16} are 65μH. L_{19} and L_{20} are 8·5μH. L_{13} is 33μH.

(3) L_{14} is wave wound, winding length ¼in.

(4) L_{17} and L_{18} are wound with their earthy ends together and spaced by 1mm.

(5) L_{21} and L_{22} are wave wound one over the other, winding length ¼in, L_{22} next to the former.

(6) L_{23} is close layer wound, L_{24} and L_{25} are bifilar wound, spaced by one wire diameter. The space between the windings is 4·5mm.

All other coils are close layer wound.

'Plumbicon'* Camera Tubes and their Applications

The 'Plumbicon' tube is a recent type of television camera tube possessing the valuable characteristics of high sensitivity, low dark current, a fast response which is independent of the luminance of the scene being viewed, and a small size relative to other types of camera tube. This article discusses the 'Plumbicon' tube and its operation and compares the performance of these tubes with that of both the image orthicon and the vidicon which were used in the majority of television cameras until the introduction of 'Plumbicon' tubes.*

'Plumbicon' television camera tubes have many advantages over the other camera tubes in most applications, but this fact appears even more notably in colour television cameras. A brief description of a three-tube colour television camera is given, again comparing similar cameras using the alternative tubes: both the optical and electronic systems are described.

Available and planned 'Plumbicon' tubes are listed.

A comparison of 'Plumbicon' tubes and vidicons under closed circuit television conditions is also appended.

INTRODUCTION

The heart of any television camera is the camera tube, where an optical image is converted into a pattern of electrostatic charges, which is scanned by an electron beam to produce electrical signals. The camera tubes which have been generally used in the past are the image orthicon and the vidicon using an antimony trisulphide photoconductive layer.** The development of the 'Plumbicon' tube makes another type of camera tube available. This tube, like the vidicon, is based on the photoconduction principle, and is constructed in almost the same way. However, the use of a different photoconductive layer with an appropriate method of operation has almost completely removed the drawbacks of the vidicon—poor response speed and high dark current—while retaining its useful features.

The 'Plumbicon' tube can thus be used for purposes where only the image orthicon has been suitable. The picture quality of the 'Plumbicon' tube compares well with that of the image orthicon, so that it is possible to put to good use in the studio the practical advantages which made vidicon tubes so attractive in other fields.

While the 'Plumbicon' tube is an attractive proposition for use in monochrome television, its special features prove to be even more favourable for colour. One of the most important reasons behind the development of the 'Plumbicon' tube was the need for a camera tube more suitable for colour cameras than either the image orthicon or the vidicon.

Principle of Operation

Externally, a 'Plumbicon' camera tube is about 213mm (8in) long and 34mm (1·25in) in diameter. The useful sensitive area is 20mm (0·8in) in diameter.

The electrode layout and principle of operation of the 'Plumbicon' tube are similar to that of the vidicon. A diagram of the target of the 'Plumbicon' tube is given in Fig. 1. The target section consists of a glass faceplate, a transparent conductive layer of stannic oxide (SnO_2) on the inner side of the faceplate, and a photoconductive layer of lead monoxide (PbO) deposited on the conductive film. The SnO_2 conductive layer is electrically connected to the signal electrode. An image of the scene is projected on to the target, the other side of which is scanned by the electron beam. The beam electrons are accelerated by anode a_2, and a mesh screen a_3 is provided to make the field between the target and a_2 more uniform.

As the electron beam scans the target, it effectively breaks the target up into a large number of elements. Each of these elements is electrically equivalent to a capacitor in parallel with a resistor as shown in Fig. 2. The value of the resistor varies with the intensity of illumination on the target, decreasing with increasing illumination.

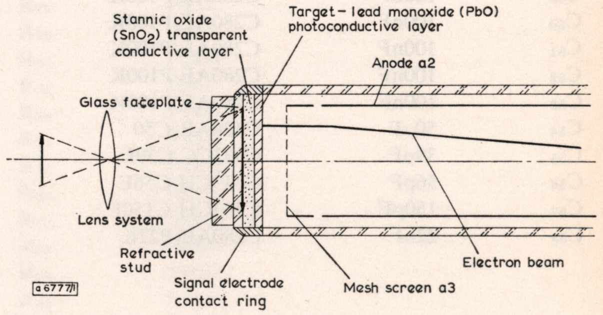


Fig. 1—Schematic diagram of target section of 'Plumbicon' camera tube

During operation, the target elements are all connected through the signal electrode to a load resistor R_L and a positive supply of about 45V. As the electron beam scans the photoconductive surface of each target element, this surface acquires approximately the potential of the cathode, usually 0V. The capacitor discharges through the elementary resistor during the remainder of the scanning period until the electron beam repeats its scan. When this occurs, the potential of the negative electrode of the elementary capacitor will again be reduced to that of the cathode. The charge that has leaked away will be restored, and thus a charge current flows to the signal electrode each time the beam completes the circuit to a target element.

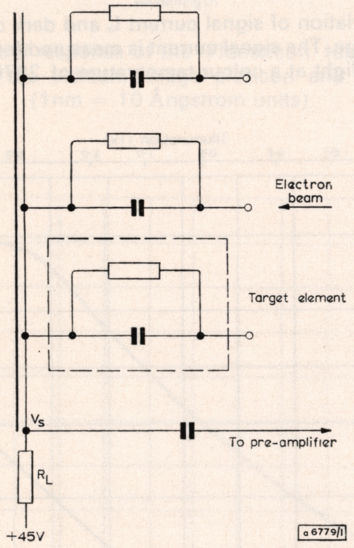


Fig. 2—Equivalent circuit of target

In darkness, the charge current is low and is termed the dark current. When a target element is illuminated, the value of the elementary resistor is low and more charge leaks away during the scanning period. The charge current is therefore greater. During continuous scanning the composite current flowing through R_L is a continuous representation of the optical image on the target. Thus the signal voltage V_S, which is negative-going for highlights, is the video signal and is fed to the preamplifier.

Photoconductive Layer

The main difference between the 'Plumbicon' tubes and the vidicons at present available is the photoconductive layer. Not only is this layer in the 'Plumbicon' tube constructed from a different photoconductor—lead monoxide (PbO) instead of antimony trisulphide (Sb_2S_3) or selenium (Se)—but the PbO layer consists of three layers of different conductivities. The middle sublayer is almost pure lead monoxide which is an intrinsic semiconductor. The surface of the PbO layer which is scanned by the electron beam is doped to make it a p-type semiconductor. Contact between the stannic oxide transparent conductive layer and the lead monoxide layer gives rise to a thin n-type layer. The doped layers are both thin in comparison with the total thickness of the lead monoxide layer. Thus the photoconductive layer of the 'Plumbicon' tube is in principle a p-i-n diode.

Examination under an electron microscope shows the lead monoxide layer to be porous in structure; it is built up of crystallites having dimensions of about $1{\cdot}0\times1{\cdot}0\times0{\cdot}1\mu$m, and the filling factor ranges from 30 to 50%. The thickness of the layer is 10 to 20μm. Thus neither the thickness of the layer nor the dimensions of the crystallites limit resolution in the 'Plumbicon' tube (the distance between two adjacent television lines being 20μm for the 625-line system).

Complete storage of the information present in the light beam is achieved if the discharging time-constant of the target is greater than the field period. Therefore the specific resistance of the photoconductor must be large, and is in practice greater than $10^{10}\Omega$/cm. However, other important characteristics of the tube—dark current and other spurious signals, resolution, sensitivity to incandescent light (largely determining the signal-to-noise ratio), spectral sensitivity and speed of response—are all mainly governed by the physical properties of the photoconductive layer.

An ideal pick-up tube would be one in which every picture element gave a signal which was dependent only on the light intensity projected on that particular element, within the required time limits. In addition, the signal from the ideal tube would be unaffected by disturbing effects such as the dark current and lag (or persistence) of the photoconductor found in the vidicon, and the dark halo and shading signals found in the image orthicon. In these respects, the 'Plumbicon' tube approaches the ideal tube, and is superior to all pick-up tubes previously used.

Dark Current

When the 'Plumbicon' tube is in operation, its photoconductive layer operates as a reverse-biased p-i-n diode. The photoconductor dark current is the inverse current through this diode, and exhibits a diode characteristic; that is, the current reaches saturation as the target voltage is increased. The dark current of the tube is very low, and is the sum of the photoconductor dark current and the leakage current between the target and anodes a_2 and a_3. The absolute variation of the dark current is small, and thus extremely good black-level uniformity is ensured. This is especially important when the 'Plumbicon' tube is used in colour television cameras.

Intrinsic Layer

The high sensitivity of the 'Plumbicon' tube is due to the intrinsic layer of the photoconductor between the p- and n-type layers. In this intrinsic region, the conductivity is low and the electrical field strength is high, so that all

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* 'Plumbicon' is a Registered Trade Mark for Television Camera Tubes.

**Other materials can be used for the photoconductive layer of the vidicon, but antimony trisulphide is the most common. Where 'vidicon' is used in this article, it refers to an antimony trisulphide type unless otherwise stated.

This article is based on articles originally published in **Philips Technical Review.** See Refs. 7, 8, 9, 10 and 11.

the liberated charge carriers in this region of lead monoxide contribute to the photocurrent if the target potential is high enough.

If a simple p-n junction were used, the requisite field strength would be available only in the immediate vicinity of the junction, and a large proportion of the liberated charge carriers would be ineffective.

A high sensitivity can therefore be obtained by making the intrinsic layer as thick as possible. However, the thicker the intrinsic layer the lower is the resolving power for red light. This is because red light penetrates the lead monoxide layer further than blue light, and consequently red light is scattered more, as shown in Fig. 3. The shaded areas indicate schematically the extent of the zones penetrated by red and blue light (R and B). Some diffused light escapes from the front face of the target, but is reflected back by the front of the glass faceplate. Red light is mainly responsible for this contribution to loss of definition. Thus the optimum thickness of the intrinsic layer is to a certain extent a compromise between good sensitivity and resolution.

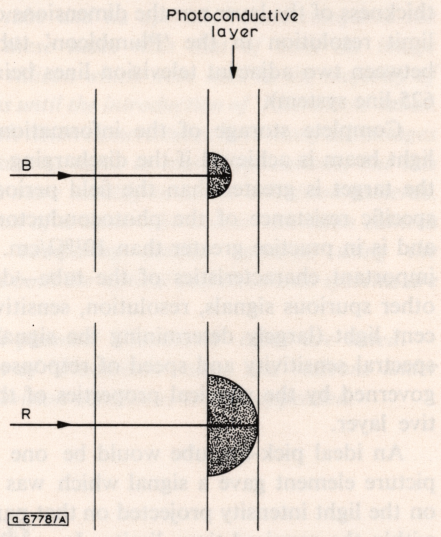

Fig. 3—Comparison of diffusion of red light and blue light

Sensitivity

The variation of the signal current of a 'Plumbicon' tube with target voltage (with the illumination constant) shows a diode characteristic, in the same way as the dark current; both reach saturation with increasing target voltage (Fig. 4). Thus for target voltages greater than the knee voltage the sensitivity of the tube is not increased, and an operating target voltage of 45V is recommended.

A typical transfer characteristic (variation of signal current I_S with illumination E) of the 'Plumbicon' tube is shown in Fig. 5, and can be represented mathematically by

$$I_S \propto E^{\gamma}.$$

Thus γ is the slope of the transfer characteristic if it is plotted on logarithmic scales as in Fig. 5. Since the graph is a straight line, γ is constant and has a value between 0·9 and 1 for a signal current up to 1μA. Thus the sensitivity of the tube can be quoted in μA/1x (or μA/1m) without specifying the illumination at which it was mesured, and a sensitivity of 300μA/1m (at a colour temperature of 2870 K) can easily be obtained. Thus, even for illumination values of 110 to 130lux on the scene, high-quality images can be obtained at lens settings of f/2·8. The quality of these images is comparable to that obtained with image orthicon cameras at f/5·6 for the same depth of focus, because of the larger diameter of the image orthicon target. A more detailed comparison is given on page 248.

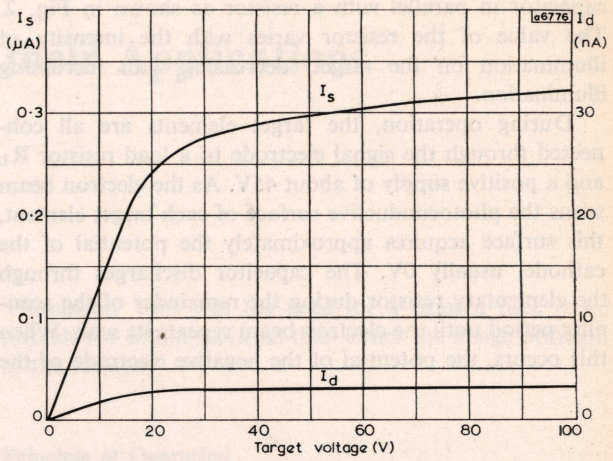

Fig. 4—Variation of signal current I_s and dark current I_d with target voltage. The signal current is measured for incandescent light at a colour temperature of 2870 K

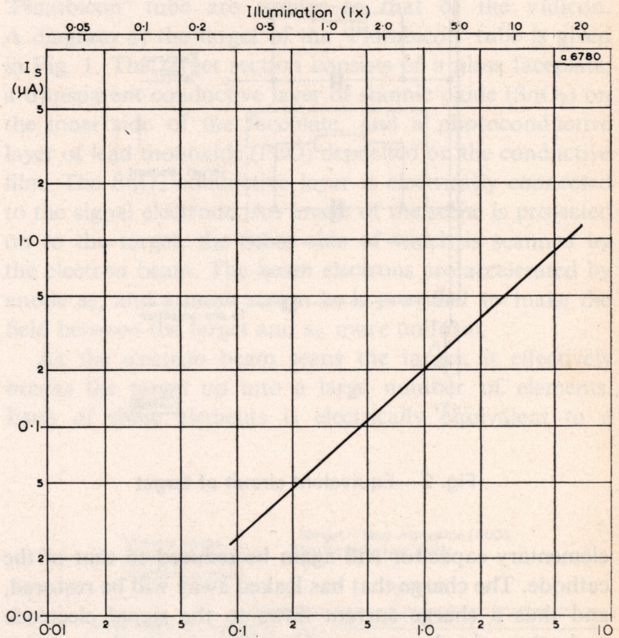

Fig. 5—Typical transfer characteristic: variation of signal current with luminous flux (in millilumens) and illumination (in lux)

Because the γ of the 'Plumbicon' tube is constant, the tube is very suitable for colour television, and excellent colour rendering can be expected over a large range of lighting conditions.

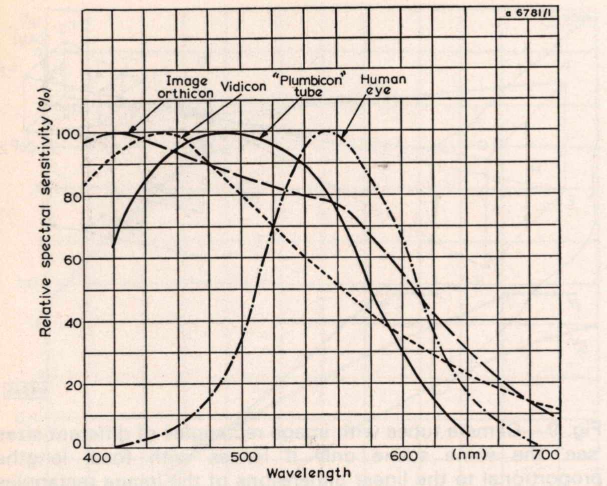

Fig. 6—Spectral response of the 'Plumbicon' tube compared with that of the vidicon, image orthicon and human eye (1nm = 10 Ångstrom units)

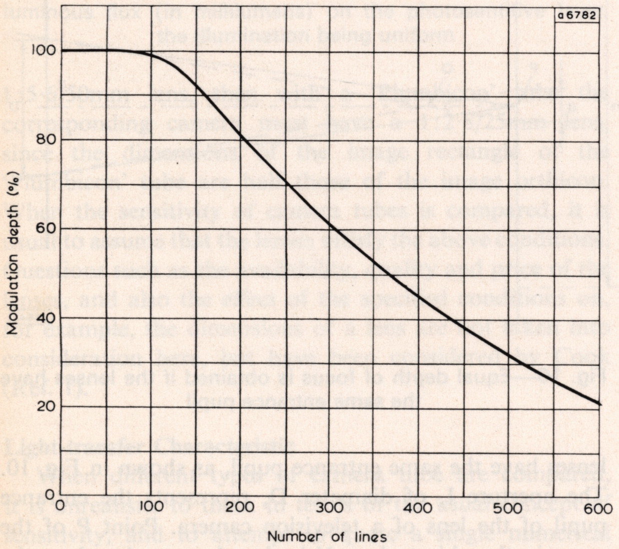

Fig. 7—Variation of modulation depth with the number of lines for a square-wave test pattern

Spectral Response

The spectral response of the 'Plumbicon' tube is shown in Fig. 6, and is compared with the spectral response curves of a vidicon, an image orthicon and the human eye. The maximum spectral response of the 'Plumbicon' tube is at approximately 500nm, and is closer to that of the human eye than that of either the image orthicon or the vidicon. The sensitivity falls off at shorter wavelengths because, as already mentioned, lead monoxide does not absorb light of all wavelengths to the same degree; the shorter the wavelength, the greater is the absorption.

Resolution

The horizontal resolution of a television camera tube can be expressed by the modulation depth at 5MHz as a percentage of the modulation depth at 0·5MHz (which corresponds to 400 lines in the 625-line system). This is measured with a bar chart. The variation of modulation depth with the number of lines for a typical 'Plumbicon' tube is shown in Fig. 7. A modulation depth of 45% can be obtained, and this figure is comparable with the resolution of a standard three-inch image orthicon.

Lag

In the 'Plumbicon' tube, the lag of the photoconductor is hardly noticeable. When the tube is operated at a target potential such that the photocurrent is saturated, the signal level reaches 95% of its steady value only 60ms (3 fields) after a change in illumination. The absence of objectionable lag results from:

(i) the capacitance of the photoconductive layer being low, so that the discharge time of the target element is short, and

(ii) the elimination of 'traps' in the intrinsic region.

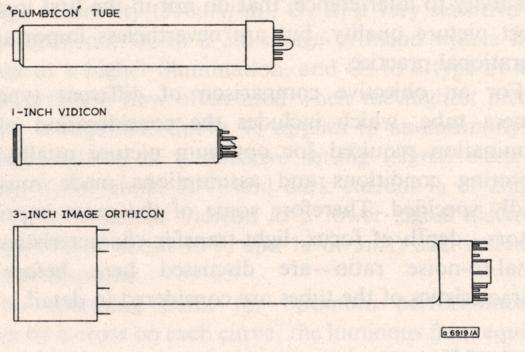

Fig. 8—Three types of camera tube: the 4½in image orthicon is often used in studio cameras, and is considerably larger than the 3in type shown

COMPARISON OF 'PLUMBICON' TUBE, VIDICON AND IMAGE ORTHICON

The users of television camera tubes now have three kinds of tube to choose from:

the image orthicon, where the optical image is converted into a pattern of electrostatic charges by means of photo-emission and secondary emission;

the vidicon, which uses photoconduction to form the charge pattern;

the 'Plumbicon' tube, having the same principle of operation as the vidicon, but a different photoconductive layer.

In the past, only the image orthicon and vidicon have been available, and the characteristic features of these tubes differ considerably. As shown in Fig. 8, the vidicon is much smaller than the image orthicon, and other advantages are its simple adjustment, stability and price. Nevertheless, image orthicons are widely used because vidicons have a number of drawbacks that can seriously impair the quality of the picture. Their speed of response under normal lighting conditions is so slow that pictures of moving objects are blurred, and they may also have a fairly high dark current. Under certain conditions, and particularly at normal illumination levels in the television studio, these undesirable effects can be so serious that acceptable picture quality becomes unattainable.

The 'Plumbicon' camera tube has all the advantages of the vidicon but none of the fundamental disadvantages, and it can therefore be used for many applications where previously only image orthicons have been suitable.

COMPARISON CONDITIONS

The objective comparison of two types of tube differing so widely in their operation and characteristic features as the 'Plumbicon' tube and the image orthicon is a complicated undertaking. It is virtually impossible to take into account and compare all the factors that determine the quality of a television picture, such as resolution, tonal graduation, brightness range, signal-to-noise ratio and uniformity, particularly as personal preference and habit also influence the eventual assessment of the picture. It is equally difficult to find a common denominator for features such as warming-up time, stability, life, and sensitivity to interference, that do not in the first instance affect picture quality, but are nevertheless important in operational practice.

For an objective comparison of different types of camera tube, which includes the consideration of the illumination required for optimum picture quality, the operating conditions and assumptions made must be rigidly specified. Therefore some of the most important factors—depth of focus, light-transfer characteristics and signal-to-noise ratio—are discussed here before the characteristics of the tubes are considered in detail.

Depth of Focus

Fair comparison between different camera tubes must relate to conditions in which the cameras pick up exactly the same scene, both foreground and background, and moreover, with the same depth of focus. It can easily be shown that the tubes will 'see' the same scene only if lenses with focal lengths proportional to the linear dimensions of the image rectangles are used. In Fig. 9 a television camera with its lens on the line OO′ is assumed to pick up a scene in which the image rectangle PQRS in the object plane V is sharply reproduced on the image rectangle $p_1q_1r_1s_1$ of the camera tube. If a second television camera having a camera tube with a larger image rectangle $p_2q_2r_2s_2$ is to take exactly the same scene (that is, the same foreground and background), its lens must be placed in position OO′, and the rectangle PQRS must be sharply reproduced on the larger image rectangle. The diagram shows that this is so if the image distances b_2 and b_1, and hence because of the large reduction, the focal lengths f_2 and f_1 are in the same ratio as the heights of the image rectangles h_2 and h_1:

$$f_2/f_1 \simeq b_2/b_1 = h_2/h_1.$$

The image rectangle of image orthicons is 24×32mm, while that of the 'Plumbicon' tube is 12·8×17·1mm, and that of most vidicons is about 9×12mm.

The depth of focus will be the same in each case if the lenses have the same entrance pupil, as shown in Fig. 10. The aperture I, of diameter D, represents the entrance pupil of the lens of a television camera. Point P of the scene in the object plane V is sharply reproduced on the photosensitive layer (not shown) of the camera tube. Point Q gives, on this layer, a spot of diameter d′ that coincides with the image of a disc of diameter d around point P, since each ray through Q and I behaves like a ray originating from this disc. If H is the height of the rectangle in V that is reproduced on the photosensitive layer as the image rectangle of height h, then

$$d'/h = d/H;$$

that is, d/H is a measure of the relative blurring of points Q belonging to the foreground or background. Hence, when one camera is replaced by another, with I in the same position, the relative lack of definition, and thus the depth of focus, remains the same, provided that D is the same.

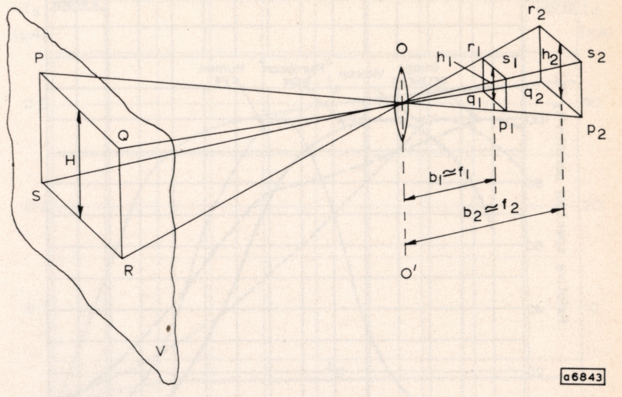

Fig. 9—Camera tubes with image rectangles of different sizes 'see' the same scene only if lenses with focal lengths proportional to the linear dimensions of the image rectangles are used

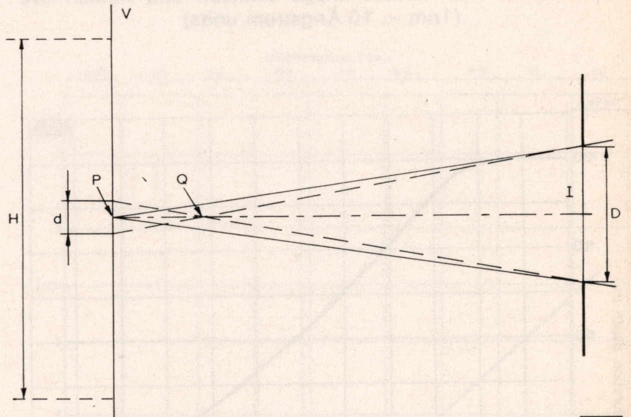

Fig. 10—Equal depth of focus is obtained if the lenses have the same entrance pupil

In practice the focal length f, and the relative aperture D/f of every lens are known. The condition of equal entrance pupil means that the product of focal length and relative aperture must also be equal. If a scene is reproduced with an image orthicon camera which has a 1:5·6/50mm lens, then with a 'Plumbicon' tube the corresponding camera must have a 1:2·8/25mm lens, since the dimensions of the image rectangle of the 'Plumbicon' tube are half those of the image orthicon. When the sensitivity of camera tubes is compared, it is usual to assume that the lenses satisfy the above conditions. Questions such as the availability, quality and price of the lenses, and also the effect of the specified conditions on, for example, the dimensions of a lens are not taken into consideration here, but have been considered by Cook (Ref. 1).

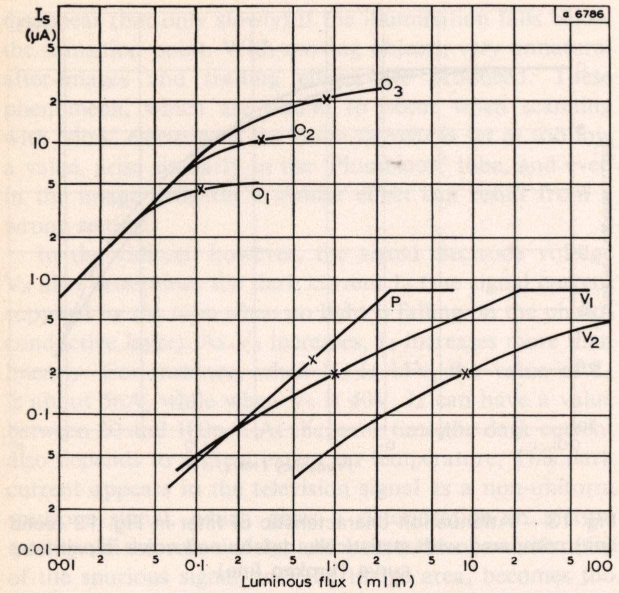

Fig. 11—Light transfer characteristics of different camera tubes. The signal current I_s is plotted as a function of the luminous flux (in millilumens) on the photosentitive layer, the illumination being uniform

Light-transfer Characteristic

When different types of camera tube are compared, it is unrealistic to think in terms of the usual concept of sensitivity, and to attempt to quote a single numerical value. One of the essential factors in the sensitivity of a camera tube is its light-transfer characteristic. This gives the signal current I_S as a function of illumination E at the photoconductive layer. Fig. 11 shows examples of such characteristics for the 'Plumbicon' tube, a vidicon, and three different types of image orthicon. These characteristics are plotted with logarithmic scales for both coordinates, so that a straight line indicates that the signal current is proportional to the power of the illumination; that is

$$I_S \propto E^\gamma,$$

and the constant exponent γ is given by the slope. If the slope is unity, which is the case over a wide range of the characteristics of the image orthicon and 'Plumbicon' tube, I_S is proportional to E.

The horizontal axis in Fig. 11 shows the reduced illumination (in millilumens); that is, the product of the illumination and the area of the image rectangle. This is the only way in which camera tubes with different image rectangles can be directly compared, for, provided that the illumination of the scene and the depth of focus are the same, this quality is independent of the size of the image rectangle. (If the tubes 'see' exactly the same scene with lenses of the same entrance pupil diameter—the specified condition for fair comparison—the values of the illumination in lux at corresponding points on the photoconductive layer are inversely proportional to the areas of the image rectangles. Thus the product of the illumination and the area of the image rectangle is independent of this area.)

Nevertheless, comparison of the light-transfer characteristics should be made with some caution. The signal current of the image orthicon, for instance, is much greater than that of the 'Plumbicon' tube or vidicon, but this does not necessarily imply greater sensitivity. The secondary-emission multiplier built into the image orthicon provides this large signal current. The real criterion for the sensitivity is the position of the optimum operating point and the related value of illumination. It will be shown that one of the most important factors in the choice of operating point is the signal-to-noise ratio in the television signal.

Characteristic P applies to a 'Plumbicon' tube of average sensitivity (350µA/lm), O_1 to a very sensitive 3in image orthicon, O_2 to a 3in image orthicon with a knee voltage at a higher illumination, and O_3 to a type of 4½in image orthicon now often used when the highest picture quality is required. Curve V_1 applies to an antimony trisulphide vidicon at a sensitive setting (signal electrode voltage V_S of about 40V, and dark current I_d of 20nA), and V_2 to a similar vidicon at a lower signal electrode voltage (V_S of about 15V, and I_d of 5nA) and increased speed of response.

The operating point for optimum performance is shown by a cross on each curve; the luminous flux required for this setting can be read on the abscissa. Various designs of image orthicon are employed, and will be discussed in greater detail later. Characteristics are shown for a vidicon at two different settings, and for a 'Plumbicon' tube of average sensitivity; the factors affecting the choice of operating point will now be discussed in greater detail.

Signal-to-noise Ratio

The signal-to-noise ratio of a television camera signal is generally taken to be the ratio between the useful signal S and the effective value N of the noise (the ratio is often expressed in dB). If S appears as a signal current, N is also considered as a noise current. If the noise in the signal is independent of S, the signal-to-noise ratio is proportional to S, so that a given situation may be characterised by the value S_W/N alone, where S_W is the signal provided by the brightest part of the scene.

The effective value of noise N can however be a function of S. This is so in the image orthicon, but in the 'Plumbicon' tube the variation of noise with signal level is even greater because of the application of non-linear amplification for gamma correction. Therefore, in the following comparison, an *equivalent noise* N_{eq} will be used, which is independent of S, and provides the same visual impairment as the actual noise. With the aid of statistical data and subjective assessments made by observers, Theile and Fix (Ref. 2) have found that a useful expression for N_{eq} is

$$N_{eq} = \tfrac{1}{6}(N_W + 3N_G + 2N_B), \qquad \ldots(1)$$

where N_W, N_G and N_B represent the effective values of noise in the signal corresponding to white, mid-grey (the signal equal to 40% of that of white) and black (for example, 2% of white) respectively.

Another important factor in the determination of the signal-to-noise ratio is the frequency spectrum of noise referred to as 'noise character'. It is well known that high-frequency noise gives much less impairment than low-frequency noise. Several workers (Refs. 2, 3 and 4) have attempted to analyse this visual difference, and reduce it to numerical or graphical terms that could be used as a measure of the impairment given by different noise frequencies. These differences in impairment become even more significant if pictures with widely differing noise spectra are to be compared, or if noise measurements have to be made on signals having differing noise frequency spectra.

In image orthicons, the output current of the multiplier is so large that the noise contribution in the signal current comes entirely from the tube itself. This noise is almost independent of frequency, so that the noise spectrum is practically a horizontal line. This is termed white or *flat* noise.

Both the vidicon and 'Plumbicon' tube deliver much smaller signal currents, and the noise contribution originates almost entirely from the very sensitive input circuit of the electronic-signal amplifier. Such input circuits are designed for a minimum of noise, and this has the result that the noise is no longer independent of frequency. In most cases, the effective noise current increases practically linearly with frequency, and is said to have a *triangular* noise spectrum.

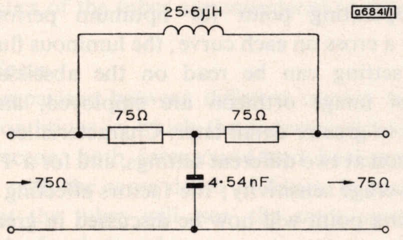

Fig. 12—Filter that can be used to take the visual impairment effect of noise into account in noise measurement

$$Q(f) = 10 \log (1 + \omega^2 t^2) \text{dB}$$

The component values have been selected so that t equals 0·33µs (CCIR recommendation)

In noise measurements, use is often made of a *noise-weighting filter,* whose transmission-frequency curve approximates very closely to the average curve for the visual impairment effect of noise. Fig. 12 shows such a filter, and Fig. 13 the resulting noise-weighting curve.

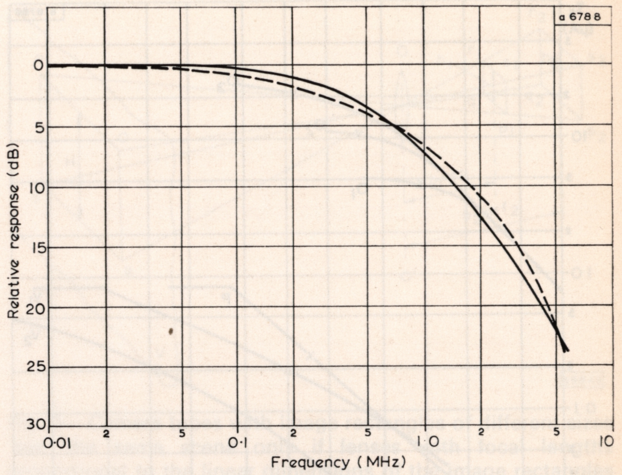

Fig. 13— Attenuation characteristic of filter in Fig. 12 (solid line) compared with statistically determined noise impairment curve (broken line)

However, to compare the image orthicon, with its flat noise spectrum, and the 'Plumbicon' tube with its triangular noise spectrum, it is simpler to use a single numerical value for the relative impairment (noise-weighting factor). This numerical value, which gives the difference between the impairment effect of flat and triangular noise, may be set at 2·25 (7dB) for a bandwidth of 5MHz. Noise measurements made without a noise-weighting filter will give signal-to-noise ratios for the 'Plumbicon' tube and vidicon which are 7dB lower than those for the image orthicon, for equal noise visibility.

CHARACTERISTICS AND OPERATING POINT OF VIDICONS

The light-transfer characteristic of a camera tube is always affected, to a certain extent, by the d.c. voltages on the electrodes of the tube. In the vidicon, the characteristic is particularly dependent on the signal electrode voltage V_S. This is clearly shown in Fig. 11, which shows characteristics for two values of V_S. Because of this dependence, the characteristic can be adapted to the illumination over a considerable range. Fig. 11 shows the vidicon characteristics as slightly curved lines of slope varying between about 0·8 and 0·4. It can be seen from the characteristic for low values of V_S, that, as the illumination increases, I_s shows slight saturation, and the characteristic gradually becomes horizontal. The characteristic for a high V_S shows a sharp transition to a horizontal line. The transition occurs at a point where the photocurrent has become so large that the electron current in the scanning beam (beam current) is no longer capable of stabilising the photosensitive layer at cathode potential. This therefore is an unstable state. If the beam current is increased, this transition point is shifted towards a higher value of I_s.

This point should never be exceeded because, in addition to loss of contrast on a horizontal characteristic, the unstabilised whites in the picture appear as washed-out areas with a tendency to spread or 'bloom'. These disappear (but only slowly) if the illumination falls below the transition point. With moving objects, very unnatural after-images and trailing effects are produced. These phenomena, which are bound to occur when scanning with 'slow' electrons if the beam current is set at too low a value, arise similarly in the 'Plumbicon' tube, and even in the image orthicon a similar effect can result from a wrong setting.

In the vidicon, however, the signal electrode voltage V_S also determines the dark current I_d (the signal current supplied by the tube when no light is falling on the photoconductive layer). As V_S increases, I_d increases more than linearly. For instance, when V_S is 15V, the value of I_d is about 5nA, while when V_S is 40V, I_d can have a value between 20 and 100nA. At the same time the dark current also depends to a great extent on temperature. This dark current appears in the television signal as a non-uniform spurious signal, which gives a deterioration in picture quality. If the value of I_d, and hence the non-uniformity of the spurious signal over the image area, becomes too great, it may be necessary to supply an electronic correction signal to compensate for the non-uniformity.

The speed of response depends almost entirely on the illumination E, and increases as E increases. Two factors limit the speed of response: the beam current lag, which depends both on the electron beam scanning mechanism and on the illumination (discharge lag), and the photocurrent lag. Thus it takes a little time for the current through the photoconductive layer to respond to a change in illumination.

The slow response at low illumination levels, which is a characteristic of the vidicon, is due entirely to photoconductive lag. However, the lag in a 'Plumbicon' tube is of a completely different nature. It does not depend on E, and is only slightly affected by V_S; above a certain value of V_S, the photoconductive lag is negligible in relation to the discharge lag.

Operating Point

The interdependence of various characteristics makes it difficult to specify one suitable operating point for the vidicon. The choice cannot be made without a more thorough analysis of the effects of the operating point on picture quality. It is therefore simpler to select a few situations, and examine the effects of a chosen setting on characteristics such as sensitivity, lag and picture quality. What is evident from such an examination is the tremendous flexibility of the vidicon, since it is possible to deal with a considerable range of illumination by adjusting V_S alone. This means that completely automatic cameras can quite easily be made.

A situation in which attempts are made to obtain the best picture quality merits special consideration. A useful signal current of I_s of 0·2µA results in (i) a very good signal-to-noise ratio, (ii) a dark current I_d of 5nA, which is sufficiently low in relation to I_s, and (iii) a sufficiently high illumination level at the photoconductive layer to ensure fast response. Under these conditions, V_S will be between 10 and 20V (depending on the temperature and the differences between individual vidicons), and the approximate luminous flux in the layer will be about 10 millilumens, corresponding to an illumination of the layer of about 80 lux.

Another situation, where the picture quality may still be regarded as acceptable, but where slow response effects may become objectionable, and I_d has increased to about 10% of I_s, is obtained with values of V_S between 30 and 40V. For I_s values of 0·2µA, and hence I_d values of 20nA, the luminous flux required is about 1/10 that in the previous example, and an illumination of 8 to 10 lux is required at the layer.

A very sensitive setting is obtained with values of V_S above 50V. Here I_d is 0·1 to 0·2µA and is of the same order as the useful signal current, while the slow response is extremely troublesome with moving pictures. Nevertheless, the picture quality at this setting, where an illumination of 2 to 3 lux at the layer is adequate, is still quite acceptable for many industrial applications.

CHARACTERISTICS AND OPERATING POINT OF IMAGE ORTHICONS

As already mentioned, the characteristics of the image orthicon are quite different from those of the vidicon and 'Plumbicon' tube, and a comparison is difficult. The light-transfer characteristic is only slightly dependent on voltage settings, and is determined by other factors. As shown in Fig. 11, it is possible to obtain different characteristics with the image orthicon, but these are obtained with *different types* of tube. The characteristics of a given type cannot easily be shifted by varying the settings without producing undesirable side-effects, and in practice different designs of image orthicon are used for different purposes.

The light-transfer characteristic shows that, over a certain illumination range, the signal current varies linearly with illumination, and above a certain value (the knee) it quickly becomes saturated. Unlike the vidicon, operation here is completely stable if the beam current is set so that values of brightness above the knee can still be handled. In practice this can be an important advantage. The light control, that is the setting of the operating point, is not critical, because the knee acts as an automatic signal current limiter. It is therefore possible to handle a wide variety of scenes in which there are marked differences in the brightness of the white portions, including specular highlights, without altering the setting. It is, moreover, possible to suit most of the scenes to be taken to the limited brightness image of the television system without difficulty. However, to obtain the best picture quality, the illumination of the sensitive layer, the photocathode, must be very carefully adjusted. This is done with the aid of adjustable diaphragms and grey filters. The optimum setting or operating point of an image orthicon is at or just over the knee. As a general rule the best setting is obtained when the illumination on the layer is such that the white parts of a scene in which a certain amount of detail must still be shown, are just above the knee of the characteristic.

A further advantage, which will not be discussed in detail here, but which is extremely important in setting-up, is the increased resolution obtained when the knee is exceeded. It is rather difficult to define resolution here, but the same physical cause that gives rise to the knee in the characteristic of an image orthicon also gives rise to apparently enhanced contours at black-to-white transients. (The physical cause is in fact a redistribution of the electrons forming the charge pattern.)

Because the optimum setting is at or just above the knee, the signal-to-noise ratio of the most sensitive type of image orthicon (with the knee at the lowest illumination) is relatively poor. Fig. 11 shows that, of the various designs, the most sensitive provides the weakest signal current. The signal-to-noise ratio, which is entirely determined by the camera tube, and is proportional to the square root of the signal current, is thus at its worst for this type. The development of image orthicons over the past few years has been directed towards shifting the knee to obtain a better signal-to-noise ratio. The most significant improvement has been the 4½in image orthicon, which has a higher knee than the 3in type, a better signal-to-noise ratio, better resolution, and which can pick up a greater range of brightness without undesirable side-effects.*

The response speed is limited only by the discharge lag. At the optimum setting this lag is quite small; it becomes noticeable only under poor lighting conditions, where the operating point is a long way below the knee.

A disadvantage is that a certain amount of burn-in with stationary pictures, rather than speed of response with moving pictures, sets the limitation. Whenever an orthicon camera has been directed on one scene for some time, say a few minutes, a burnt-in image is formed, which can render the camera useless for a while. If it is used by inexperienced operators, this effect can even cause irreparable damage to the tube.

Fig. 11 shows that a 4½in image orthicon at the optimum setting is only half as sensitive as a comparable 3in design. It has, however, an improved signal-to-noise ratio: in a 3in tube this is 36dB, while in a 4½in model it can be as much as 39dB.

CHARACTERISTICS AND OPERATING POINT OF THE ‘PLUMBICON’ TUBE

At low signal electrode voltages V_S, the light-transfer characteristic exhibits a shift similar to that of the vidicon. However, because of the special properties of the photoconductive layer, the signal current rapidly becomes saturated as V_S increases. Above a signal electrode voltage of 45V, sensitivity virtually ceases to increase, and thus when V_S is greater than 45V the characteristic can be considered as fixed. If the illumination is increased with V_S constant, then, as with vidicons, there is a point where there is a sharp transition to a horizontal line, because the beam current is no longer adequate to stabilise at cathode potential. Of course, it is also possible to shift this transition point of the ‘Plumbicon’ tube by varying the beam current.

One of the main differences between the ‘Plumbicon’ tube and vidicon is that, in the stable region, the light-transfer characteristic of the ‘Plumbicon’ tube is a straight line of unity slope, which means that I_s is proportional to E. Only in this case can the sensitivity be indicated by a single numerical value, expressed in μA/lm. The sensitivity of a ‘Plumbicon’ tube lies between 300 and 400μA/lm.

Optimum Setting

A discussion of the optimum setting of a ‘Plumbicon’ camera tube will be considered first, and a more quantitative treatment will follow. In the image orthicon the operating point is entirely determined by the knee of the characteristic, which also determines the signal-to-noise ratio, permissible brightness range and sensitivity. For the vidicon, the choice of operating point is a compromise between speed of response, dark current and the quantity of light available. For the ‘Plumbicon’ tube it will be shown that the optimum setting is likewise determined by the effects of various factors.

As already mentioned (pages 245 and 247) the ‘Plumbicon’ tube has two main advantages over the vidicon. In the first place, the dark current is negligibly low and does not become very much greater at higher values of V_S. Secondly, the photoconductive lag is very small and independent of illumination. The photoconductive lag is to some extent dependent on V_S, but at usual values of V_S it is negligible compared with the discharge lag.

Because of these advantages, finding the optimum setting is simple. If the operating point is made low, the illumination required is also low (that is, the sensitivity is high), and the signal current is small, while the signal-to-noise ratio is poor. With a higher operating point, more light is needed, but the signal current becomes proportionally larger, and the signal-to-noise ratio proportionally better.

The amount of noise in the signal has thus become practically the only decisive factor in the choice of setting, and all factors affecting this noise therefore directly affect the choice of operating point.

As described for the vidicon, an inadequate beam current can cause a sharp transition in the characteristic to a horizontal line, giving rise to an unstable state of ‘over-exposure’. With the linear characteristic of the ‘Plumbicon’ tube the risk of over-exposure due to a sudden increase in the illumination level or to specular highlights is higher than with the vidicon characteristic, which exhibits saturation. This must be given careful consideration, which means that the risk of over-exposure must be reduced by stopping down, using grey filters or adjusting the level of illumination of the scene. With a camera equipped with a ‘Plumbicon’ tube, it is therefore of utmost importance to have a fast and accurate light control. However, it is extremely difficult, if not impossible, to prevent accidental specular highlights, and these too must not give rise to over-exposure. The knee in the characteristic must therefore be far enough above the operating point to leave an adequate safety margin. The knee can be shifted upwards by increasing the beam current, but this can prejudice resolution. Therefore, in view of the safety margin required, it is recommended that the operating point never be set higher than is necessary to obtain an acceptable signal-to-noise ratio.

Quantitative Determination of Operating Point

The signal current necessary to obtain a given picture quality will now be discussed in more detail. The starting point is the signal-to-noise ratio, since it is an important factor, as shown above. The signal-to-noise ratio of the output signal will be assumed to be 40dB for flat noise—a value which can hardly be attained with the best image orthicons, and which is generally considered fully adequate for studio use. As shown on page 250, the most significant source of noise in both the vidicon and ‘Plumbicon’ tube is the input circuit of the signal amplifier, and this noise is frequency-dependent. If the signal-to-noise ratio is to be at least 40dB for flat noise, then for triangular noise the ratio S/N of the peak signal current to the effective noise current must be at least 100:2·25 or 45:1.

Fig. 14 shows the elements of a camera signal amplifier that affect the signal-to-noise ratio of the output signal.

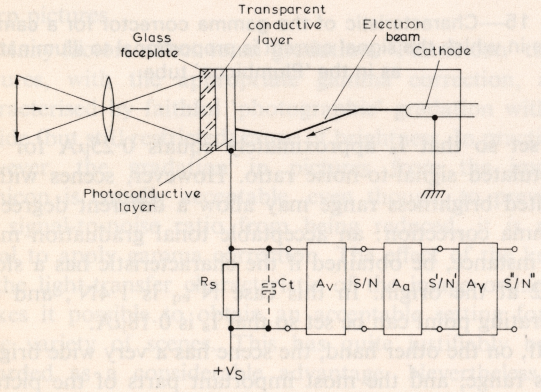

Fig. 14—Connection of a ‘Plumbicon’ tube (or vidicon) to preamplifier A_v by means of signal resistor R_s. The equivalent noise resistance of the input stage of A_v, and the parasitic capacitance C_t limit the signal-to-noise ratio at the output of A_v. V_s is the signal electrode voltage, and A_a and A_γ are circuits for aperture and gamma correction respectively

The elements are the preamplifier A_v, the aperture corrector A_a, and the gamma corrector A_γ. The preamplifier is always necessary; aperture and gamma correction are not always required, depending to some extent on the circumstances.

The camera tube, whose inherent noise can be neglected, is connected to the preamplifier A_v by means of signal resistor R_S. Analysis shows (Ref. 5) that as the value of R_S increases—if the output impedance of the camera tube is assumed to be infinitely high—the signal-to-noise ratio at the output of A_v approaches a maximum given by

$$\frac{S}{N} = 22\times10^8 \frac{I_s}{FC_t\sqrt{(FR_t)}} \qquad \ldots(2)$$

where F is the bandwidth, R_t the ‘equivalent noise resistance’ of the input circuit of the preamplifier, C_t the total parasitic capacitance in parallel with R_S, and the constant 22×10^8 is the value at room temperature of

$$\sqrt{\left(\frac{3}{16\pi^2 kT}\right)}.$$

It can be seen from Eq. 2 that, at a given bandwidth, C_t and R_t set a limit to the value of S/N, and also that the value of C_t is of prime importance. With practical values (F, 5MHz; C_t, 25pF; and R_t, 200Ω), Eq. 2 gives

$$\frac{S}{N} \simeq 5{\cdot}6\times10^8\, I_s.$$

Thus a minimum signal current of 80nA (for white) is needed to obtain at the output of A_v a signal-to-noise ratio of 40dB (S/N is at least 45). In practice, because of the noise contribution from R_S, a slightly worse ratio must be taken into account, and the actual value of I_s is 0·1μA. (It is possible to make the values of C_t and R_t smaller by using more complex preamplifier circuits with selected components, and a very accurate setting (Ref. 6)).

EFFECT OF APERTURE CORRECTION

The resolution of the picture is determined by a number of factors. It depends to a great extent on limitations in the camera tube itself, but the optical section can also be significant. In particular, zoom lenses (lenses with continuously variable focal length), which are now often used, are certainly not ideal at large apertures. Spot correction or, as it is more often called, aperture correction, which compensates for the effective size of the electron beam scanning spot exceeding the line width, can improve resolution. A simple electronic circuit giving amplification increasing with frequency, without the introduction of phase errors, can give optimum resolution at least in the horizontal direction (Ref. 7). Aperture correction gives no amplification at low frequencies, so that the signal amplitudes over large areas of the picture do not alter with the insertion of A_a, but the higher signal frequencies, and hence the higher frequencies in the noise spectrum, receive extra amplification.

At 5MHz, the modulation depth of the average ‘Plumbicon’ tube is only 50% of its value at 0·5MHz, so that the amplification at 5MHz must be at least twice as great (6dB more) for optimum correction. Further analysis shows that this causes the signal-to-noise ratio with a triangular noise spectrum to decrease by a factor of 1·3. If, therefore, the original assumed value of 40dB for the signal-to-noise ratio is to be retained, and full use made of the increased resolution obtained by aperture correction, I_s must be increased to 0·13μA.

Resolution has thus been improved at the expense of sensitivity. If enough light is available, this optimum correction is of course desirable, but if lighting is poor (as for example during the evening), a compromise must be made between resolution and noise, by suitably setting the aperture correction.

EFFECT OF GAMMA CORRECTION

The aperture correction mentioned above is also often used in vidicon cameras. Gamma correction is, however, required only for ‘Plumbicon’ tubes. This is because, in a picture tube, the luminance of the screen increases with the square (at least) of the signal voltage applied to the control grid of the tube. To make the screen luminance proportional to the luminance of the original scene, the output signal of the camera must be approximately proportional to the square root of the scene luminance. This is approximately what happens in the vidicon because, in the light-transfer characteristic

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*Other factors, apart from the target size, affect the position of the knee, so that various designs of both the 3in and 4½in types are possible. Most of the characteristic features of the latest 3in types approximate very closely to those of the average 4½in type, and, although the signal-to-noise ratio and resolution are basically better in the 4½in type, the differences have become so slight that both types are used side by side.

$$I_s \propto E^{0\cdot16},$$

and E is, of course, proportional to the luminance of the scene. The proportionality of the image orthicon is not so good, but the effect of the knee, and the additional effect that the average scene content has on the characteristic, make gamma correction seldom necessary.

In the 'Plumbicon' tube, however, where I_s is proportional to E, and no limitation or saturation occurs up to the point of instability, the gamma corrector A_γ is essential. This consists of a non-linear amplifier in which the output signal S″ and the input signal S′ are connected by the relationship

$$\frac{S''}{S''_W} = \left(\frac{S'}{S'_W}\right)^{\gamma}, \qquad \ldots(3)$$

where the subscript W indicates the signal for white. The characteristic is shown in Fig. 15. In theory, the characteristic must always be a curve with infinite slope at the origin (since γ is smaller than unity), but in practice a slope of 4 at the origin is sufficient for good tonal gradation (shown by the dotted line).

The amplification S″/S′ is dependent on the signal level, and is given by the slope of the chord to the origin (ignoring the constant factor S''_W/S'_W). The noise N′ superimposed on S′ is also amplified, but this amplification is determined by the slope of the tangent at the appropriate point. For a parabolic characteristic (γ equals 0·5 in Eq. 3), it can easily be verified that the amplification of the signal is always twice that of the noise.

In spite of this, gamma correction reduces the signal-to-noise ratio. Although by definition a noise level N′ is assumed to be independent of the signal level S, the amplification of the noise does depend upon the signal level. The equivalent noise will therefore be calculated using Eq. 1 (page 250):

$$N''_{eq} = \tfrac{1}{6}(N''_W + 3N''_G + 2N''_B).$$

N''_B is determined by the practical consideration that, in a practical gamma corrector, the tangent will never be vertical. If the characteristic has a slope of 4 at the origin, and gradually becomes a parabola, excellent tonal gradation is also obtained in the dark parts of the picture. In this case

$$N''_B = 4N'.$$

Moreover, for white

$$N''_W = 0\cdot5N',$$

and in the grey (for which it is assumed that S″ is $0\cdot4S''_W$)

$$N''_G = 1\cdot25N'.$$

Therefore

$$N''_{eq} \simeq 2N'.$$

Thus gamma correction reduces the normalised signal-to-noise ratio by half, and, to maintain the desired signal-to-noise ratio of 40dB, this must be offset by a proportional increase in the signal current I_s.

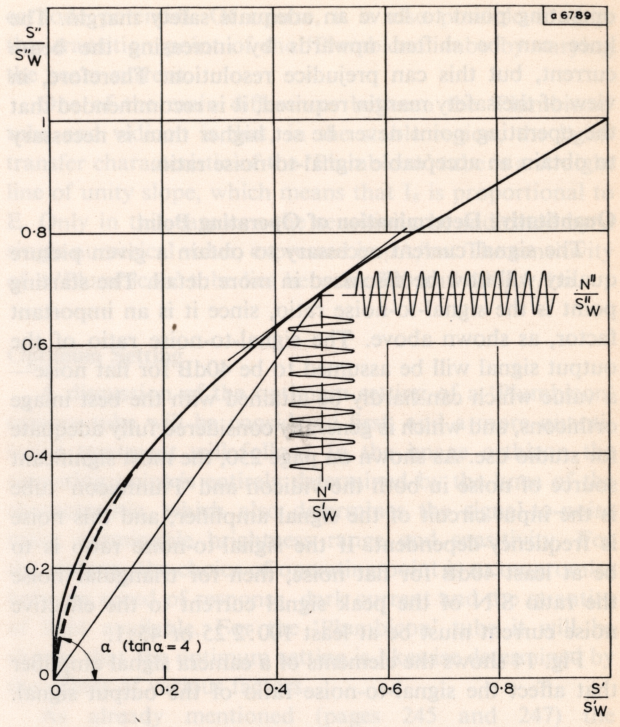


Fig. 15—Characteristic of the gamma corrector for a camera tube in which the signal current is proportional to illumination as in the 'Plumbicon' tube

Therefore, if both aperture and gamma correction are used with a 'Plumbicon' tube, the operating point must be set so that I_s approximately equals 0·25μA for the postulated signal-to-noise ratio. However, scenes with a limited brightness range may allow a different degree of gamma correction: an acceptable tonal graduation may, for instance, be obtained if the characteristic has a slope of 2 at the origin. In this case N''_{eq} is 1·4N′, and the operating point can be set so that I_s is 0·18μA.

If, on the other hand, the scene has a very wide brightness range, and the most important parts of the picture are dark, the operating point may have to be set at a higher I_s to prevent the noise in the dark parts from being too pronounced at maximum gamma correction. The extent to which this can be done (if at all) will depend on the safety margin required to allow for specular highlights, which, as discussed on page 252, can cause the characteristic to enter the unstable state if the beam current is inadequate.

COMPARISON BETWEEN THE 'PLUMBICON' TUBE AND IMAGE ORTHICON

As mentioned on page 248, it is impossible to make a purely objective comparison between different types of camera tube. It is in fact quite reasonable not to attempt any comparison between the vidicon and image orthicon, since these two types of tube are used for quite different purposes. The 'Plumbicon' tube, however, does not have the fundamental limitations of the vidicon, and can therefore be considered for the same applications as the image orthicon. Thus it is both possible and useful to compare the 'Plumbicon' tube and image orthicon. The comparison will be restricted to some of the characteristic features of particular importance: sensitivity, resolution, tonal gradation and signal-to-noise ratio.

Fig. 11 and the calculation of the operating points have already shown that the sensitivity of the 'Plumbicon' tube is approximately comparable to the best 3in image orthicons. Inspection of a large variety of scenes confirms this in practice. The 'Plumbicon' tube is, however, more sensitive than the 4½in image orthicon, especially since the sensitivity of image orthicons decreases as the number of operational hours increases, and sometimes even drops to half during life.

The situation is different for resolution. Without special correction the resolution of the 'Plumbicon' tube is not as good as that of the 4½in image orthicon. The image orthicon, correctly operated at the knee of the characteristic, benefits here from the apparent 'contour-enhancing' effect mentioned on page 252, which accentuates transitions from black to white. The perceptible differences between the two types of tube do, however, diminish considerably if aperture correction is used, which is fairly simple for the horizontal direction. The differences also depend upon the beam current setting, and even the colour temperature of the light has some effect: outdoor scenes with a high colour temperature taken with a 'Plumbicon' tube often give surprisingly sharp pictures.

Many factors affect tonal gradation. 'Plumbicon' tube pictures, with the appropriate gamma correction, are characterised by faithful 'photographic' gradation within a wide (but still restricted) range of brightness. In practice, however, the gradation in pictures from the image orthicon is equally acceptable, even though, to prevent the signal-to-noise ratio from being reduced, it is not usual to apply gamma correction. The effect of the knee in the light-transfer characteristic of the image orthicon makes it possible to obtain an acceptable setting for a wide variety of scenes. This has quite justifiably been regarded as a considerable advantage. Nevertheless, a better result can generally be obtained with a 'Plumbicon' camera tube equipped with a signal limiter and an adjustable gamma corrector.

It is only in scenes with a very wide brightness range or with specular highlights that situations occur which adversely affect the picture quality of the 'Plumbicon' tube—either by loss of resolution, or by trailing effects in the non-stabilised highlights or by increase of noise in the image—because the operating point must be set to a lower signal current.

The signal-to-noise ratio for a given type of image orthicon is determined by the tube itself, and (when noise is measured without a noise-weighting filter) is 34 to 36dB for a 3in type, and 37 to 39dB for a 4½in type, depending on the setting and operational life. The illumination needed for the 'Plumbicon' tube in the discussions so far has been calculated on the basis of a signal-to-noise ratio of 40dB. Here is one of the most important differences between the image orthicon and the 'Plumbicon' tube. The signal-to-noise ratio of a given image orthicon can be improved only very slightly. If more light is available, the operating point cannot be shifted, since the knee in the characteristic would cause all gradation in the lighter parts of the image to disappear. With the 'Plumbicon' tube, however, the operating point can be displaced along the characteristic, so that, if desired, the signal-to-noise ratio can be still further improved.

This shows that, for applications where high picture quality is called for and where the ordinary vidicon cannot be used because it is not sensitive enough, the 'Plumbicon' tube is an interesting proposition. It can, in many instances, produce pictures of a quality comparable to those of the best image orthicon.

COLOUR TELEVISION WITH 'PLUMBICON' CAMERA TUBES

The 'Plumbicon' camera tube has a number of features which allow the development of a colour television camera with these tubes to be approached in a different way from the design of a camera with image orthicon tubes. This is true for the optical and also for the mechanical and electronic design. With the much smaller dimensions of the 'Plumbicon' tube and its associated system of deflection and focusing coils, a new colour separation system can be used which is not only optically better than previous systems, but also, because of its small size, permits a completely new mechanical design to be used for the camera. The result is a colour camera which is no larger or heavier than many conventional black-and-white cameras. The main relevant features of the 'Plumbicon' tube are a linear tube characteristic, which is little affected by temperature and voltage fluctuations, a signal current which is virtually free from noise and interfering components, and a black level which is nearly constant owing to the negligibly low dark current. In this article we shall see how these features have been taken into account in the design of a colour television installation (Refs. 8 and 9).

A studio or outside broadcast television installation almost always consists of two parts: the camera, mounted on a movable stand, and the control unit in the control room. These two parts are connected together by a cable containing a large number of single cores and several coaxial leads. For outside broadcasts, this cable may be hundreds of yards long. All electrical adjustments are kept together at the control unit where they are under the control of a technician who keeps watch on picture quality. The cameraman is only concerned with aiming and focusing the camera. Colour television installations are similarly divided. Obviously, as the electronic section of such installations is rather large every attempt is made to include as much of it as possible in the control unit.

Fig. 16 shows the camera with the 'Plumbicon' tubes which we shall discuss here. The zoom lens in its housing, which also contains the servo drives, can be seen on the left. On its immediate right may be seen the small, encapsulated colour separation system, and the 'Plumbicon' tubes, oriented in three different directions, with their deflection and focusing coil assemblies and preamplifiers. The remaining space in the camera is occupied by amplifiers and timebase circuits. The handle used for aiming the camera carries the servo controls for focusing and for choosing the focal length of the zoom lens. The associated

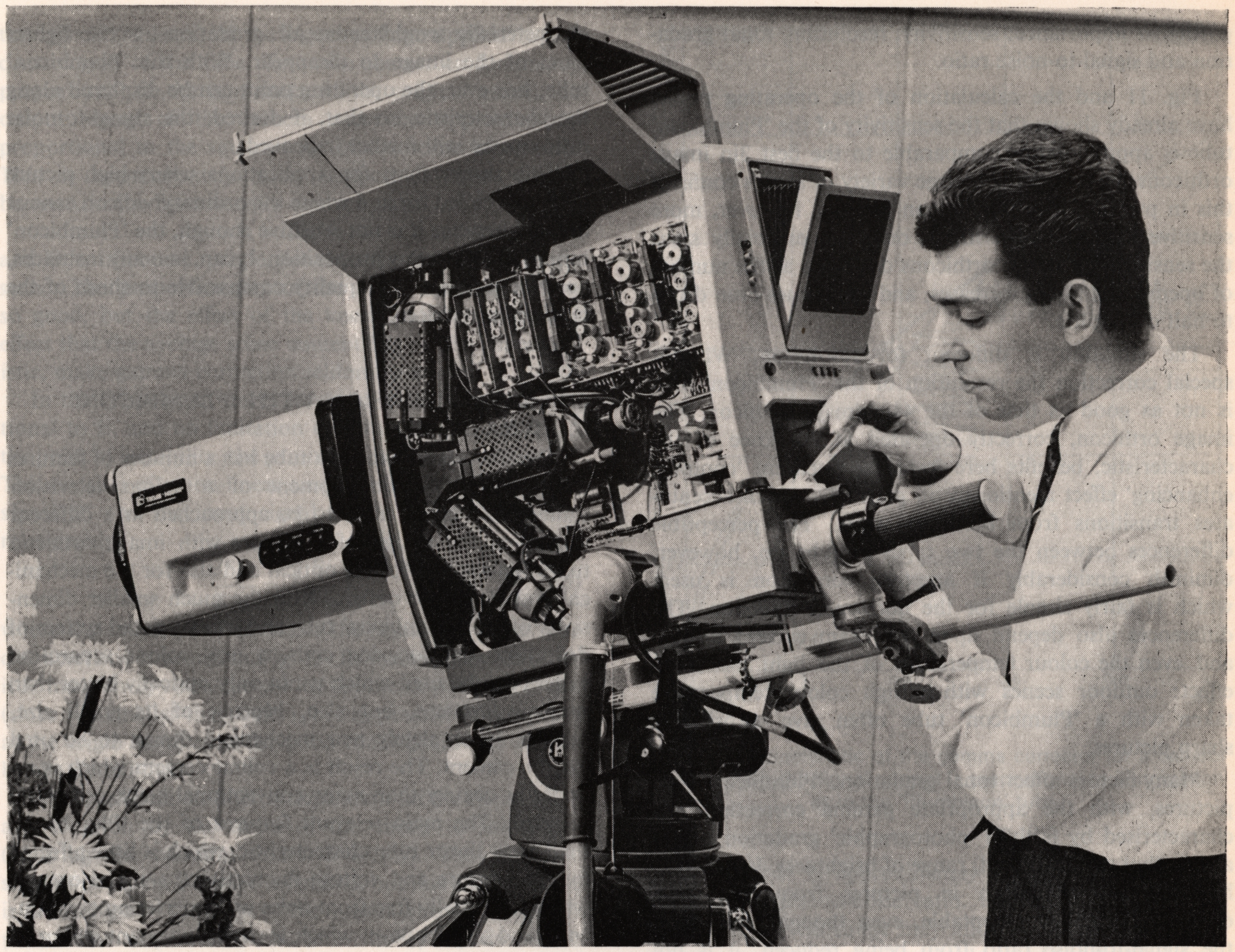


Fig. 16—The camera open but otherwise ready for use

control unit, which will also be discussed briefly, is described later.

Before discussing the camera, let us first briefly recapitulate the simultaneous colour television system on which all colour television studio installations are now based. The cone of light which enters the camera through the lens is distributed in three directions by a set of two colour-selective mirrors so that only a certain wavelength range of the visible spectrum passes in each direction. This gives rise to three cones of light containing the red, green and blue colour extracts from the received image. The mirror system does not affect the convergence of the rays of light to form a sharp image in the image plane, and sharp and geometrically congruent images in the primary colours, red, green and blue are therefore produced on three identical camera tubes arranged in the cones of light.

The colour signals R, G and B derived from these tubes by the normal scanning process form the basis for the later reconstruction of the complete colour picture in the receiver. These signals set up three pictures in the primary colours red, green and blue in accurate geometrical register on the receiver screen, and the simultaneous presence of these pictures gives the impression of a picture in natural colours (additive mixing).

Camera

The components of every colour television camera can be divided into three groups: the camera lens with the colour separation system; the pick-up section with the camera tubes and their deflection and focusing coils; and finally the electronic circuits. While the problems encountered in the first group are almost entirely optical ones, the second group requires attention to precision engineering, and the third group comes in the province of the electronic engineer. A few of the problems arising in these widely varying fields will now be dealt with.

Camera Lens and Colour Separation Systems

An essential difference between black-and-white and colour cameras is that the back-focus distance of the camera lens in a colour camera must be very long so that the colour separation system can be inserted between the lens and the camera tubes. (The back-focus distance of a lens system is the distance between the image plane and the rearmost portion of the system, which is generally the holder of the final component lens.) Such a system consists of the colour-selective mirrors mentioned above, which divert for example the red and blue cones of light, while the green is allowed to pass through directly to the 'green' camera tube (Fig. 17). The red and blue cones are reflected again by ordinary plane mirrors so that they take up a direction parallel to the main optical axis before they arrive at the appropriate camera tubes.

Fig. 17—Colour separation principle in television cameras. L is the camera lens; M_b and M_r are colour-selective mirrors; M_1 and M_2 are ordinary plane mirrors.

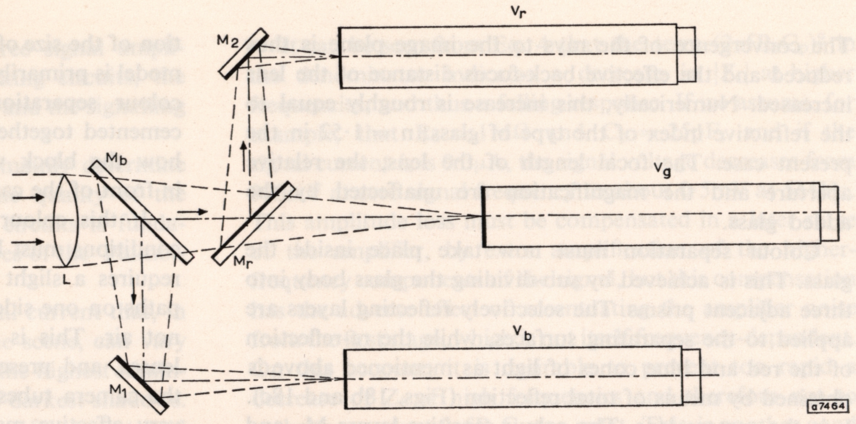
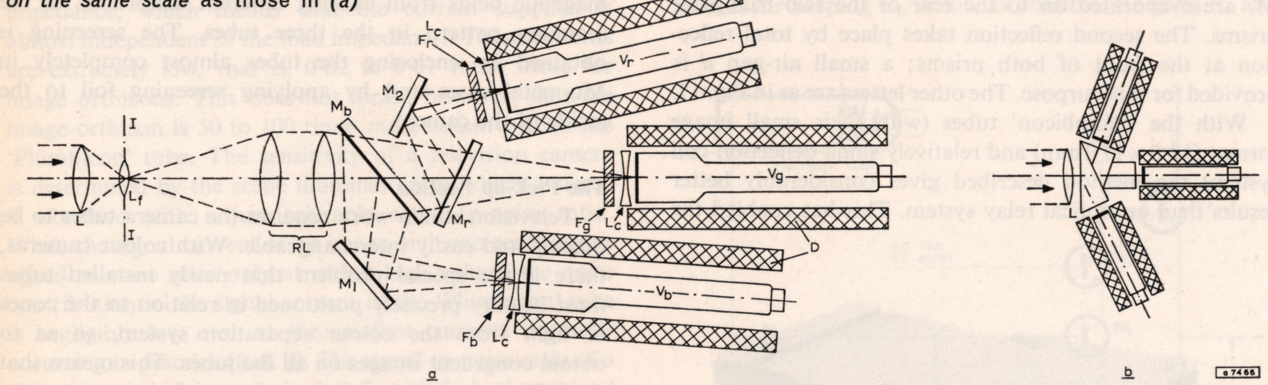


Fig. 18—Practical arrangement of the colour separation systems in *(a)* image-orthicon cameras, *(b)* the 'Plumbicon' tube colour camera, the components being illustrated here *on the same scale* as those in *(a)*



The double reflection is important as it eliminates the lateral inversion which occurs in single specular reflection. This inversion could also be compensated by reversing the direction of scan in the camera tube. However, as the coil systems never have completely symmetrical deflection characteristics, there would be differences in geometry between the normally scanned green image and the red and blue images scanned in the opposite direction. It is virtually impossible to correct for these differences, and the three primary colour pictures on the receiver screen would therefore not be completely in register.

The parallel arrangement of the camera tubes also assists the accurate register of the three pictures. With this arrangement, the effects of the Earth's magnetism or any other interfering fields on the deflection system are much the same for all three tubes, so that distortions of the scanning are similar for all three pictures.

In the camera described here these interfering effects are reduced adequately in another way, described below.

A colour separation system like that shown in Fig. 17 requires so much room between the camera lens and the tubes that lenses with unsuitably long focal lengths and rather small relative apertures would have to be used. In image orthicon cameras, this difficulty is overcome by the addition of an optical system of long focal length (the relay system) which transfers the intermediate image obtained with a normal camera lens across the required large distance to the camera tubes. This is shown in Fig. 18a. L is the camera lens. To allow lenses with a large relative aperture and normal focal lengths to be used, an optical relay system RL is included. A focal length here of about 150mm gives sufficient clearance for the colour separation system. L_f is the field lens for concentrating the light beam in the optical relay system. The curvature of the image produced by L_f is compensated by the three correction lenses L_c. F_r, F_g and F_b are colour-correction filters to limit more sharply the wavelength ranges separated by the colour-selective mirrors. D represents the deflection and focusing coil systems. The other letters are as in Fig. 17.

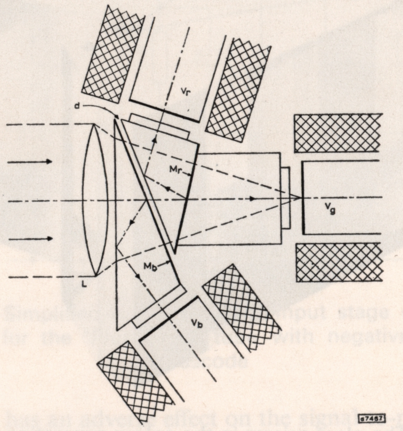


Fig. 18*c*—Prismatic colour separation system of the 'Plumbicon' tube camera, shown on a larger scale than in Fig. 18*b*

The small dimensions of the 'Plumbicon' camera tube allowed the development of a different method, described in Ref. 10, for this colour television camera. In this method the free space between the camera lens and the tubes is filled with glass in the path of the light beams.

The convergence of the rays to the image plane is thus reduced and the effective back-focus distance of the lens increased. Numerically, this increase is roughly equal to the refractive index of the type of glass; n = 1·52 in the present case. The focal length of the lens, the relative aperture and the magnification are unaffected by the added glass.

Colour separation must now take place inside the glass. This is achieved by sub-dividing the glass body into three adjacent prisms. The selectively reflecting layers are applied to the separating surfaces, while the re-reflection of the red and blue cones of light as mentioned above is obtained by means of total reflection (Figs. 18b and 18c). L is the camera lens. The colour-sensitive layers M_b and M_r are evaporated on to the rear of the two triangular prisms. The second reflection takes place by total reflection at the front of both prisms; a small air-gap *d* is provided for this purpose. The other letters are as in Fig. 17.

With the 'Plumbicon' tubes (with their small image format (12·8×17·1mm) and relatively small deflection-coil system) the method described gives considerably better results than an optical relay system. This has enabled the 'Plumbicon' colour camera to be used with first-class lenses of aperture up to f/2 and a focal length down to 18mm. These are the same as the values used with black-and-white cameras.

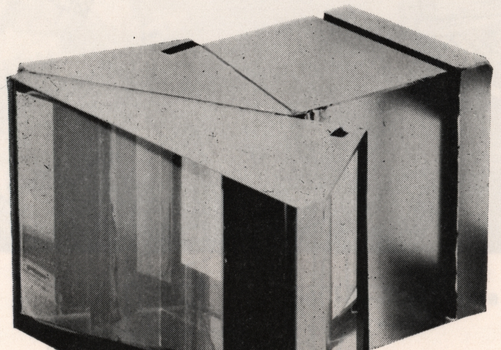


Fig. 19—The glass prisms in the colour separation system are cemented together to form one unit about 35mm high

Because the number of optical components, and hence the number of transitions from glass to air, has been reduced to a minimum, the light losses of the entire optical system, which can amount to more than 50% in relay systems, are greatly reduced here, to about 20%. Moreover, definition and contrast of the image are considerably improved by the use of this method. Another advantage is that the light strikes the two colour-selective reflecting layers at relatively small angles. This means that polarisation effects, which can lead to colour errors, particularly if there are specular reflections (Ref. 10), occur only to a very slight extent. Finally, as we noted earlier, the reduction of the size of the camera to that of a black-and-white model is primarily due to the compactness of the prismatic colour separation system. Fig. 19 shows the prisms cemented together to form a block, while Fig. 16 shows how the block with its protective housing is arranged in front of the camera tubes.

If this colour separation system is to be used, two conditions must be satisfied. First of all, the camera lens requires a slight additional correction because the light paths on one side of the lens are almost entirely in glass, not air. This is a matter for the manufacturers of the lenses, and presents them with no difficulties. Secondly, the camera tubes, which are not parallel, must be given very effective magnetic screening to prevent interfering magnetic fields from causing different distortions of the scanning pattern in the three tubes. The screening is obtained by enclosing the tubes almost completely in Mu-metal cases and by applying screening foil to the inside of the camera.

The Pick-up Section

Television studio work requires the camera tubes to be quickly and easily interchangeable. With colour cameras, there is the special problem that newly installed tubes must be very precisely positioned in relation to the cones of light from the colour separation system, so as to obtain congruent images on all the tubes. This means that the following conditions have to be satisfied:

1) The optical axis of each of the three cones must coincide with the longitudinal axis of the appropriate tube.

2) The three image planes of the lens must coincide with the surface of the signal electrode for each of the three tubes.

3) The horizontal direction in each of the three images must coincide with the direction of scan.

The mechanical design must be drawn up with this in mind, and the deflection coils and the camera tubes must be engineered to such a degree of precision that these three conditions can be met and continue to be met after a tube has been changed. In fact, the relatively simple construction of the 'Plumbicon' tube and its set of deflection coils enabled a system to be devised for changing a tube without the need for mechanical readjustment. The initial setting of the three deflection-coil assemblies is carried out with the aid of an optical alignment device which permits six different adjustments to be made for each coil assembly. These adjustments are given by displacement along and rotation about three axes which are perpendicular to one another and pass through the centre of the signal electrode of the tube. (The rotation about the longitudinal axis of the tube is not in fact made during optical adjustment but by comparison with the horizontal direction of scan.)

Although the design eliminates the need for mechanical readjustment when a new tube is put in, a certain number of electrical adjustments are still required, as the electrode systems in different tubes are never completely identical.

The Circuits

The circuits in a colour television camera may be subdivided into groups comprising the three signal amplifiers, the deflection, focusing and blanking circuits, the supply section, the electronic view-finder and the signalling and telephone circuits.

The circuits in the first two groups mainly determine the performance of the camera and the quality of the pictures obtained. The design of these circuits is fundamentally affected by the particular features of the 'Plumbicon' tube and its deflection system.

The 'Plumbicon' tube supplies a signal current that, in practice, with appropriate lighting of the scene, can vary between about 0·3μA at the points with the highest luminance and only a few nanoamperes in the darkest shadows. (The tube can be regarded as a source of high internal impedance, which means that the current supplied is almost independent of the load impedance.) These currents are extremely low, that is, 0·02 to 0·01 times those for image orthicons. This does not mean, however, that the image orthicon is 50 to 100 times more sensitive than the 'Plumbicon' tube. The sensitivity of a television camera is determined by the scene illumination at which a signal is obtained with a just tolerable signal-to-noise ratio. While the signal current of an image orthicon reaches this signal-to-noise ratio only at rather high values, the noise contribution in the signal current of the 'Plumbicon' tube is negligibly low even at the smallest currents normally occurring in practice (Ref. 9). The signal-to-noise ratio of a 'Plumbicon' tube camera is therefore entirely determined by the noise performance of the signal amplifier, which in turn is largely determined by its input stage. On this account the input stage is the one to which most attention has to be paid when designing the amplifier circuit.

To obtain a good signal-to-noise ratio, the amplifier must have as high an input impedance Z_i as possible. This can be understood in the following way. In Fig. 20, the input impedance consists of an input resistance R_i and a capacitance C_p connected in parallel. This capacitance C_p is formed by the input capacitance of the amplifier, in parallel with the signal-electrode capacitance of the 'Plumbicon' tube, and the stray capacitance of the connecting leads $|Z_i|$ (at frequency f) is then given by:

$$|Z_i| = \frac{R_i}{\sqrt{1+(2\pi fR_iC_p)^2}}\,. \qquad \ldots \quad (4)$$

Since we can regard the 'Plumbicon' tube as a constant-current source, the signal voltage v_s is proportional to Z_i :

$$V_s = i_s\,|Z_i|\,,$$

where i_s is the signal current. The noise, however, consists mainly of two contributions, one of which, the noise from the first valve or transistor in the amplifier, is independent of Z_i , while the other, originating in R_i , is given by

$$v_n = (\sqrt{4kT\Delta f})\frac{\sqrt{R_i}}{\sqrt{1+(2\pi fR_iC_p)^2}}\,,$$

where v_n=effective noise voltage, k=Boltzmann's constant, T=temperature and Δf=bandwidth. If $|Z_i|$ is increased, which, as Eq. 4 shows, may be done by making R_i greater or C_p smaller, the signal voltage increases proportionally to $|Z_i|$, while the first-stage noise contribution remains constant and the one due to R_i increases much less rapidly: the signal-to-noise ratio will therefore improve.

It can be seen from Eq. 4 that the term $(2\pi fR_iC_p)^2$ in the denominator indicates a decrease in $|Z_i|$ at higher frequencies, and thus a falling response. If we assume, for example, that R_i = 1MΩ and C_p = 25pF, and if the signal current i_s is 0·3μA, the signal voltage decreases from 300mV at zero signal frequency to about 0·5mV at 5MHz. This amplitude loss must be compensated in a later stage of the amplifier, by extra amplification of the higher-frequency components of the signal, but this compensation has the adverse effect of accentuating the amplifier noise from the first stage, which is not itself frequency-dependent. On this account, it is desirable to prevent too rapid a decrease of Z_i at high frequencies and therefore not to make the product $2\pi fR_iC_p$ too great. This is another good reason for keeping C_p as low as possible. Keeping R_i low, however, has an adverse effect on the signal-to-noise ratio, which as we have shown in the previous paragraph, requires a high value of R_i .

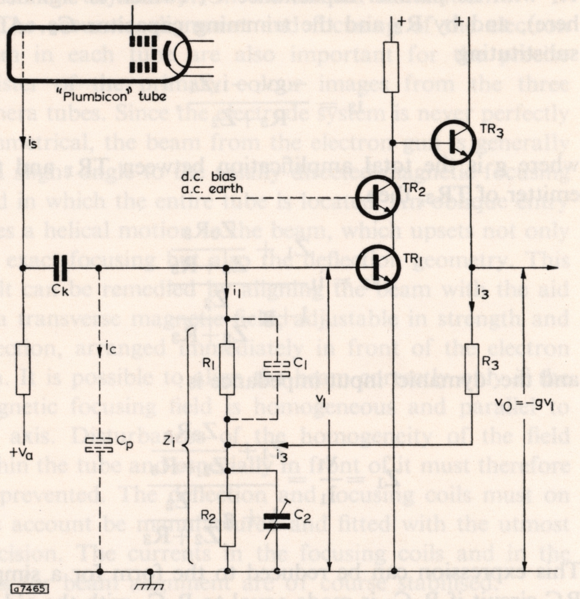


Fig. 20—Simplified diagram of the input stage of a signal amplifier for the 'Plumbicon' tube with negative feedback cascode

The two conflicting requirements for the value of R_i can be largely reconciled by the use of negative feedback, as will be seen in the following more detailed discussion of the signal amplifier.

Previously, to reduce the amplifier noise from the input stage, nuvistor input circuits (the nuvistor is a small thermionic triode system) have usually been used both for 'Plumbicon' tube cameras and vidicon cameras, although the vidicon camera has been otherwise fully transistorised. Nuvistors give considerably less noise than p-n-p or n-p-n transistors. Their noise performance has however been surpassed by that of the field-effect transistors which are now available. Moreover, these give a lower input capacitance than nuvistors. For the input stage of the signal amplifier, the present design uses a combination of a field-effect transistor and an n-p-n transistor. This gives a signal-to-noise ratio 2 to 3dB better than that obtained with a nuvistor; in an experimental version the improvement was as much as 7 dB.

The basic circuit of the input stage, a cascode circuit with feedback, is given in Fig. 20. Part of the signal voltage amplified in TR_1 and TR_2 and taken from emitter follower TR_3 is fed back to the input via R_3 and R_2. The tube, which may be regarded as a source of constant current, supplies a signal current i_s, part of which (i_c) flows through the stray capacitance C_p, while another part (i_1) passes through the input impedance Z_i of the amplifier. The amplified feedback current i_3 generates an opposite voltage, and so the control voltage v_1 is lower. The actual control voltage of TR_1 then becomes:

$$v_1 = i_1 Z_1 + (i_1 + i_3)Z_2 .$$

Z_1 and Z_2 are the impedances of the circuits formed by R_1 with its parallel capacitance C_1 (which is significant here), and by R_2 and the trimming capacitor C_2. After substituting

$$i_3 = \frac{-gv_1 - i_1Z_1}{R_3+Z_2},$$

where g is the total amplification between TR_1 and the emitter of TR_3, then:

$$v_1 = i_1 \frac{Z_1 + \dfrac{Z_2R_3}{Z_2+R_3}}{1+g\dfrac{Z_2}{Z_2+R_3}}$$

and the 'dymanic' input impedance is:

$$Z_1 = \frac{v_1}{i_1} = \frac{Z_1 + \dfrac{Z_2R_3}{Z_2+R_3}}{1+g\dfrac{Z_2}{Z_2+R_3}} .$$

This expression can be reduced to the form for a simple RC circuit if R_2C_2 is made equal to R_1C_1 with the aid of the trimming capacitance C_2 and if $R_2 \ll R_1$. Then:

$$Z_i = \frac{R_1}{1+g\dfrac{R_2}{R_2+R_3}} \; \frac{1}{1+j\omega C_1 \dfrac{R_1}{1+g\dfrac{R_2}{R_2+R_3}}} .$$

The total impedance presented to the signal current i_s supplied by the 'Plumbicon' tube is that due to Z_i in parallel with the stray capacitance C_p, and is thus:

$$Z_{tot} = \frac{KR_1}{1+j\omega KR_1(C_1+C_p)},$$

where

$$K = \frac{1}{1+g\dfrac{R_2}{R_2+R_3}} .$$

This means that, for a given amplitude-frequency response, R_1 may be 1/K times greater than in a non-feedback circuit. To put it another way, the later stages will now only have to compensate for a K-times smaller reduction in amplitude at higher frequencies.

With the circuit in question, we have obtained a signal-to-noise ratio of 45dB at the signal current of 300nA quoted above and a bandwidth of 5MHz. (In television, the signal-to-noise ratio is regarded as the ratio between the maximum signal amplitude at a black-and-white transition and the r.m.s. value of the noise. For the 'weighting' of the noise and the associated filter, see page 5 of Ref. 9. Measurement with a noise-weighting filter, as used for black-and-white television, has under the given conditions indicated a signal-to-noise ratio of as high as 60dB).

To keep the stray input capacitance C_p as low as possible, the three preamplifiers, which are printed wiring boards carrying the input stages, are each fitted directly on top of the appropriate deflection systems, giving a very short distance between input stage and signal electrode of the 'Plumbicon' tube (see Fig. 21). With this arrangement, interference due to stray electric fields at the input lead is also kept to a minimum.

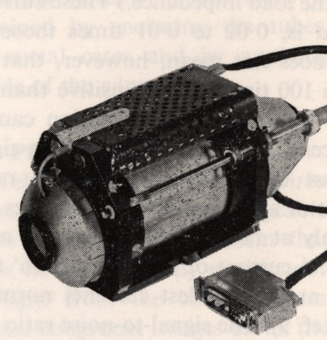


Fig. 21—Deflection and focusing coil assembly for a 'Plumbicon' tube with the preamplifier fitted to it and protected by a perforated screening plate

Each preamplifier contains only the input stage and emitter follower. From the low output impedance of the emitter follower the signals are fed via screened leads to further amplifier stages in the camera. The reduction in amplitude which we mentioned earlier is compensated in these stages, so that signal components at frequencies up to 6MHz are fed to the camera cable at equal amplitude. The level of these components lies far above that of any interference that might be picked up in the long cable between camera and control unit.

The excellent noise performance of these signal amplifiers ensures a low interference level in the picture, and their linearity and stability ensure very faithful colour rendering. Another important factor in the quality of a colour television picture is the accuracy of register of the three primary colour pictures: this is determined by the characteristics of the deflection circuits. The designs of the vertical and horizontal deflection circuits are quite different, because of the difference in scanning speed.

The vertical deflection circuit is located in the control unit and the three finally-shaped saw-tooth currents for vertical deflection in the three tubes are fed directly to the deflection coils via the camera cable. All the controls and adjustments can thus be made at the control unit. As the impedance of the deflection coils is very nearly purely resistive at the low frequency of the saw-tooth currents (50Hz), this method presents no difficulty. Sufficient stabilisation of the desired shape and amplitude of the saw-tooth currents against fluctuations in the temperature of the camera cable and the deflection coils is obtained by current feedback in the output stages of the deflection circuits.

Matters are not so simple for the horizontal deflection circuits. A pair of horizontal deflection coils requires a current with a saw-tooth waveform between −100 and +100mA and a repetition rate of 15·625kHz. The resistance R of the pair of coils is 3Ω and its inductance L is 1mH, so that the impedance at a frequency of 15kHz is $Z = R+j2\pi fL = 3+100j(\Omega)$. In order to obtain a saw-tooth current in this almost pure inductance, a pulsed voltage is required whose amplitude is given by the expression:

$$v_L = \frac{Ldi_{st}}{dt} .$$

In practice, a peak voltage of about 60V is used. Because of the ohmic resistance, a saw-tooth component

$$v_{st} = Ri_{st}$$

has to be added to this voltage (see Fig. 22).

While the value v_L determines the amplitude of the saw-tooth current, and hence the scanning width, the linearity of the saw-tooth current and the scanning sweep is governed by v_{st}. Apart from these two parameters, the position of the pulsed voltage in relation to the zero line is significant, as this determines the symmetry of the scanning sweep in relation to the vertical centre line of the signal electrode of the camera tube. This requires the addition of an adjustable d.c. component.

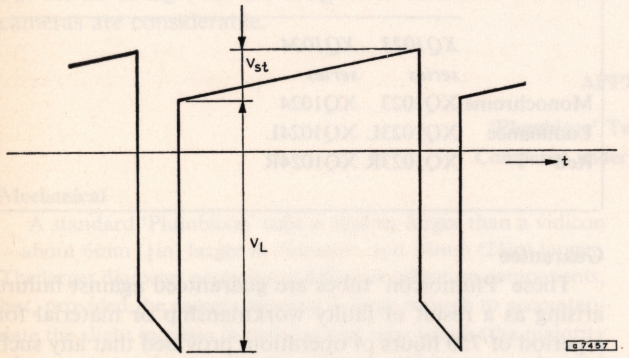


Fig. 22—The voltage waveform required for the horizontal deflection coils of a 'Plumbicon' tube. v_1 pulse voltage which sets up a saw-tooth current in the coils; v_{st} saw-tooth voltage for linearising the saw-tooth current

For practical reasons, these three important adjustments are made in the central control booth, that is at the control unit, and not at the camera. It has been usual for the basic horizontal deflection waveforms for colour cameras to be generated at the control unit, and distributed from there to the three channels. The three adjustments mentioned above for each channel were also made at the control unit and the individually adjusted waveforms were fed to the deflection coils in the camera via three coaxial leads in the camera cable. This method not only involved appreciable wastage of power on account of the 75Ω characteristic impedance of the cable (compare the coil resistance which is 3Ω); there were also considerable complications in maintaining the correct voltage waveforms when cables of different lengths and types were used and when there were temperature variations.

The development of very stable transistor circuits has made it possible to shift the whole of the horizontal deflection circuit for the colour camera with 'Plumbicon' tubes to the camera itself and so to eliminate the difficulties just mentioned. Thus only a trigger pulse for the pulse generator circuit in the camera (this pulse is not critical in shape or amplitude) and a number of d.c. voltages for the control of amplitude, linearity and the d.c. component of the scan are fed through the camera cable. The controls for these voltages are arranged on the control unit and remain thus under the charge of the technician responsible for all the adjustments in the camera installation.

The accurate alignment and focusing of the electron beam in each tube are also important for the precise register of the primary colour images from the three camera tubes. Since the electrode system is never perfectly symmetrical, the beam from the electron gun is generally at a slight angle to the axially directed magnetic focusing field in which the entire tube is located. An oblique entry gives a helical motion to the beam, which upsets not only the exact focusing but also the deflection geometry. This fault can be remedied by aligning the beam with the aid of a transverse magnetic field, adjustable in strength and direction, arranged immediately in front of the electron gun. It is possible to align the beam correctly only if the magnetic focusing field is homogeneous and parallel to the axis. Disturbances of the homogeneity of the field within the tube and especially in front of it must therefore be prevented. The deflection and focusing coils must on this account be manufactured and fitted with the utmost precision. The currents in the focusing coils and in the coils for beam alignment are of course stabilised.

The remaining circuits in the camera are similar to those in most other cameras and are not discussed in this article.

CONTROL UNIT

The control unit, connected by cables to the camera, contains the processing amplifiers with the various facilities for modifying the final video signal. Optimum colour can be arranged by balancing the three colour outputs. Registration of the three colour pictures can be adjusted and the definition of each picture can be maximised. Also in the control unit are the various means of monitoring the output signal and the final picture. All the power supply circuits are in the control unit.

In the processing amplifiers the maximum level and the zero level of each colour signal are firmly established. Extreme peaks of signal are rendered innocuous, gamma correction to suit colour television receivers is applied, and the blanking signals are applied in such a way as to meet the relevant colour television standards.

Aperture correction can be applied to each colour signal, and as a whole to the combined signal. The aperture correction for the combined signal can be used to give contour enhancement both to vertical and horizontal contours. In the design being described, the 'contours from green' system was used.

Further details of all of these facilities can be found in Ref. 10.

PERFORMANCE

The camera described, using three 'Plumbicon' tubes, requires from the scene being viewed considerably less light than is required by even a four-tube image orthicon camera. Colour uniformity is good indoors and outside, even under the poor lighting often met outside. Colour registration is better than that with image orthicons and is as good as that from a four-tube camera. The contour enhancement, using 'contours from green', equals that from a four-tube camera, while better colour uniformity is maintained than with a four-tube camera.

AVAILABLE 'PLUMBICON' TUBES

Six series of 'Plumbicon' camera tubes suitable for both monochrome and colour cameras are available:

55875 series

The 55875 series are sensitive, high-definition, integral-mesh 'Plumbicon' tubes, primarily intended for broadcast systems.

55875–IG series

The 55875–IG series tubes are industrial-grade versions of the 55875 series. They are suitable for economical industrial, medical and educational closed-circuit applications.

XQ1020 series

A recent introduction is the separate-mesh 'Plumbicon' tube, which has the mesh electrode isolated from the gun, and connected separately to its own pin termination on the tube base. This allows the mesh to be operated at a slightly higher potential than the gun, and so enables a higher beam current and more accurate beam landing to be obtained. These features give the resulting picture improved highlight-handling capability and better edge resolution. The XQ1020 series are separate-mesh 'Plumbicon' tubes primarily intended for broadcast cameras.

XQ1021 series

An industrial-grade version of the XQ1020 series is available under the type number XQ1021 series.

XQ1023 series

'Plumbicon' tube with Increased Sensitivity to Red Light

By replacing part of the lead monoxide, photoconductive layer with a mixture of lead sulphide and lead monoxide, the sensitivity of the 'Plumbicon' tube to red light can be increased. Light of all wavelengths is absorbed in the photoconductive layer of this type of tube and consequently there is no loss of definition caused by scattering of red light reflected from the target. When the tube is used in a colour television camera, the red channel is so much more sensitive than with a standard 'Plumbicon' tube that it is no longer this channel but the blue one which determines the overall sensitivity of the camera. The overall sensitivity is as much as three times higher, one result of which is a better signal-to-noise ratio of the luminance signal.

XQ1024 series

These tubes are industrial grade versions of the XQ1023 series, and have the same enhanced red sensitivity.

Application

Each tube is designed for a particular camera channel (monochrome, luminance or colour) in which it will provide an optimum performance. However, in an emergency, any tube, whatever its designation, will provide a satisfactory performance in another channel. The recommended channel is indicated by a letter in the type number:

Channel	*55875 series*	*55875–IG series*	*XQ1020 series*	*XQ1021 series*
Monochrome	55875	55875–IG	XQ1020	XQ1021
Luminance	55875L		XQ1020L	
Red	55875R	55875R–IG	XQ1020R	XQ1021R
Green	55875G	55875G–IG	XQ1020G	XQ1021G
Blue	55875B	55875B–IG	XQ1020B	XQ1021B

	XQ1023 series	*XQ1024 series*
Monochrome	XQ1023	XQ1024
Luminance	XQ1023L	XQ1024L
Red	XQ1023R	XQ1024R

Guarantee

These 'Plumbicon' tubes are guaranteed against failure arising as a result of faulty workmanship or material for a period of 750 hours of operation, provided that any such failure occurs within twelve months of the date of the supply of the tube to the ultimate user. Replacement is free if the tube fails during the first fifty hours of operation; between 50 and 750 hours the failed tube will be replaced by a new camera tube, similarly guaranteed, the price of which will be calculated in accordance with the formula

$$\text{Price of replacement tube} = P\frac{N}{750},$$

where P is the original invoice price of the faulty camera tube, and N is the number of full hours of operation before the tube failed.

Other Types under Development

Several new types of tube are under consideration and development for commercial use and two of these are mentioned below.

Electrostatically Focused 'Plumbicon' Tube

In standard 'Plumbicon' tubes and most ordinary vidicons, the electron beam is focused magnetically. In addition to the deflection coils, there is a much larger coil, which ensures that the diameter of the beam is as small as possible in the plane of the sensitive layer. This focusing coil can be omitted, and the power required for focusing reduced nearly to zero by using electrostatic rather than electromagnetic focusing. An additional advantage of this method is that the picture can be rotated, magnified or reduced in size when the focus is adjusted—a useful facility in colour television cameras. Also, in an electrostatically focused tube, deflection cannot affect the focusing. Focusing is effected by means of a unipotential lens, consisting of three cylinders with the centre one at a much lower potential than the outer two. The two outer sections may be regarded as the two separated halves of the anode cylinder a_2 of a standard 'Plumbicon' tube. This electrostatic focusing lens take up no extra space in the tube.

Tubes for Hand-held Cameras

For hand-held colour cameras, the tubes used must be small and light. For this purpose a 'Plumbicon' tube with a 16mm diameter has been developed. Additional saving of bulkiness in the camera has been made possible by using electrostatic focusing in this tube.

Other small sizes of tube are also under consideration. With all of these very small tubes the resolution is somewhat limited because of the smallness of the target area, but the advantages for the designer of miniature television cameras are considerable.

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APPENDIX

'Plumbicon' Tubes and Vidicons Compared under CCTV Conditions

Mechanical

A standard 'Plumbicon' tube is slightly larger than a vidicon —about 6mm ($\frac{1}{4}$in) larger in diameter, and 54mm ($2\frac{1}{8}$in) longer. The larger diameter necessitates different deflection components, but, provided the camera housing is large enough to accommodate the slight increase in coil size and tube length (the majority of cameras are large enough), there should be no mechanical problems.

Since the 'Plumbicon' tube retains the simple gun design of the vidicon, extensive circuit redesign will not be required when a vidicon camera is converted to use the 'Plumbicon' tube. However, cctv cameras differ in physical layout, optics and circuit design, and the following points may require some modification.

The 'Plumbicon' tube is 'back-mounted'; that is, it is inserted into its coil assembly from the rear and not from the optics side, as is the vidicon. Therefore the camera can be designed with fixed optics, and mounting plates can be eliminated. A 'Plumbicon' tube can be inserted into its coil either by means of a rear access panel in the camera, or by using a 'swing-out' coil assembly.

Optical

The recommended size of the scanned rectangle of the 'Plumbicon' tube is 12·8×17·1mm, and the optics used in the camera should be chosen so that it is possible to scan such a raster. However, it is possible to scan a vidicon-sized raster (9·6×12·8mm) on a 'Plumbicon' tube, but, under such underscan conditions, some loss of resolution will be experienced. To utilise the features of the 'Plumbicon' tube, and obtain the optimum performance from the cctv system, a 12 8×17 7mm raster is recommended.

Electrical

All the gun voltages of the 'Plumbicon' tube are identical to those of the vidicon, and hence the power supply design of the cctv system need not be changed. However, the 'Plumbicon' tube requires a *fixed* target voltage of 45V.

Because of the characteristics of the AT1113/01 deflection, focus and alignment coil assembly, some modification to the sweep amplifiers and focus-current supply of the system may be required.

Since the 'Plumbicon' tube has a gamma of 0·9 to 1·0 (compared with 0·6 for the vidicon), some modification to the gamma-correction circuitry of the system may be necessary for optimum operation.

The 'Plumbicon' tube and coil assembly may present a slightly different input impedance to the preamplifier. Care should therefore be taken to ensure that this input impedance is matched to the preamplifier.

PERFORMANCE

The 'Plumbicon' tube has many advantages over the vidicon for cctv applications, and a brief comparison of the two tubes is shown overleaf.

	'Plumbicon' Tube	**Vidicon**
Target Voltage	The properties of the 'Plumbicon' tube are independent of target voltage above the knee voltage. Operation at a target electrode voltage of 45V is recommended.	Many properties of the vidicon vary with target voltage and it is always necessary to compromise between sensitivity and dark current.
Background and Shading	The photoconductive layer of the 'Plumbicon' tube consists of a unique diode structure, which gives an extremely uniform and very low dark current (less than 3nA). Background shading effects are therefore negligible under all conditions of use.	Vidicons are normally operated at a target voltage giving 20nA dark current (although this can be even higher under low light conditions). This dark current gives rise to background shading and non-uniformity in the picture. Because it is not uniform over the scanned area of the target, and is also dependent on temperature, this shading cannot be corrected electrically.
Sensitivity	The sensitivity of an average 'Plumbicon' tube is such that a signal of 75nA is obtained with 1 lux on the target, and 700nA with 10 lux. (The gamma of the 'Plumbicon' tube is about 0·95.)	A typical vidicon at 20nA dark current has a signal current of 40nA for a target illumination of 1 lux, and 200nA for a target illumination of 10 lux. (The gamma of the vidicon is about 0·6.)
Lag	The photoconductive layer in the 'Plumbicon' tube is inherently free from lag. Under similar conditions to those for testing vidicons, the residual signal after 60ms (3 fields) is about 3% (the test limit is 5%). Lag is independent of sensitivity, and in addition the favourable performance is retained at very low levels of illumination. (As a rough guide, the lag will be increased by a factor of 2 at a target illumination of about 0·1 lux.)	Even the best vidicons under optimum conditions retain an appreciable portion of the video information for several scans, and on moving scenes this appears as objectionable smearing of the picture. Under test conditions, the residual signal after 60ms is about 12·5% for good vidicons, and may be as high as 25 to 30%. An additional disadvantage is that tubes having high sensitivity generally exhibit high lag, while conversely, tubes with good lag have low sensitivity.
Resolution	The 'Plumbicon' tube has a limiting resolution of about 750 tv lines; at a signal current of 300nA the modulation depth at 400 lines is typically 45% (at the centre) and 35% (in the corners), measured without aperture correction. Aperture correction can be used to increase the 400-line response to 100%, while retaining a fully acceptable signal-to-noise ratio in the displayed picture.	A typical integral-mesh vidicon intended for cctv has a limiting resolution of about 750 tv lines. At a signal current of 200nA, the modulation depth at 400 tv lines (5MHz) is about 45% at the centre of the picture, and 30% in the corners. These measurements are made without aperture correction.
Highlight Retention Effect	As with any photoconductive device the 'Plumbicon' tube is subject to burn-in, but the unique features of the photoconductive material used make burn-in a minor, if not insignificant, problem. Specifications call for a 'Plumbicon' camera tube to be rejected if a burn-in image does not disappear within 10 seconds of the removal of the scene.	Burn-in is frequently a severe problem in cameras equipped with vidicons, and a limit is not generally specified by the manufacturer. Users of cctv cameras often find it necessary to replace vidicons because of burn-in created by prolonged observation of bright stationary objects.
Target Blemishes	At the time of installation, a 'Plumbicon' tube is as clean as a vidicon. During use, the 'Plumbicon' tube is less likely to develop further spots and blemishes because of the very low dark current generated in the photoconductor. The acceptance test specification for blemishes is given in Ref. 11. The test chart is broken into three zones (not two as for vidicons) to ensure the best possible 'critical centre' area of the picture. In addition, for the industrial grade of 'Plumbicon' tubes, there is a limit on the total number of spots in any area.	Good quality vidicons are generally fairly 'clean' at the time of initial installation. However, during use they tend to develop more spots, especially at high dark current settings, and the blemishes tend to become larger.